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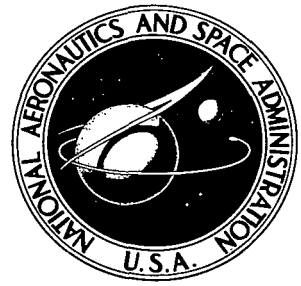

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SOLAR-DIURNAL VARIATIONS OF COSMIC RAYS FROM THE MAXIMUM TO THE MINIMUM OF SOLAR ACTIVITY

by L. I. Dorman and Ye. V. Kolomeyets

"Nauka" Press, Moscow, 1968

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SOLAR-DIURNAL VARIATIONS OF COSMIC RAYS FROM THE MAXIMUM TO THE MINIMUM OF SOLAR ACTIVITY

By L. I. Dorman and Ye. V. Kolomeyets

Translation of "Solnechno-sutochnyye variatsii
kosmicheskikh luchey ot maksimuma
do minimuma solnechnoy aktivnosti."
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ANNOTATION

The present study analyses the planetary distribution and energy dependence of the first and second harmonics of the solar-diurnal variation of cosmic rays in the quiet and disturbed periods according to the data of the world network of neutron monitors for the observation period 1957 - 1964, i.e., for the period from the maximum to the minimum of solar activity. A comparison is made with the results of other authors. The work shows that the anisotropy of cosmic rays is a sensitive characteristic of the changing conditions in interplanetary space. On the basis of the obtained data, a critical analysis is conducted of the mechanisms discussed in the literature which cause anisotropy of the galactic cosmic rays in the solar system. A model of the solar-diurnal variations of cosmic rays is developed from the theory of anisotropic diffusion of particles on the moving irregularities of the interplanetary magnetic field in the presence of a regular field, with different directions of the field with force lines in the form of the Archimedes spirals. The authors show that the obtained set of experimental data, apparently, is best correlated with this model qualitatively, and does not contradict it quantitatively.

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INTRODUCTION

The change of the intensity of cosmic rays with a period of one day was detected around 30 years ago, essentially in that period when the continuous recording of cosmic rays had only begun.

In the first approximation the flux of the primary particles is constant in time and isotropic in space, but cosmic rays entering the solar system are subjected to the electromagnetic influence of interplanetary space. This effect is caused by solar corpuscular radiation which, with its emergence from the atmosphere of the sun, carries magnetic fields with it. The latter may be represented as a quasiradial interplanetary field, against whose background there are nonuniformities of the magnetic fields. These magnetic fields, "frozen in" in the corpuscular streams, are propagated along with them and induce an electric field. The indicated electromagnetic effect on cosmic rays, taking into account the earth's rotation around its own axis, also gives the effect of a diurnal variation.

At present several points of view in respect to the direct mechanisms responsible for the solar-diurnal variations are debated, but almost all of them are based on the idea of the electromagnetic action of the interplanetary magnetic fields around the Earth on the primary cosmic radiation. Moreover, it is assumed that in specific periods, to a large extent, the asymmetric variation of the geomagnetic rigidity threshold is also responsible for the solar-diurnal variation.

In this monograph the main attention was given to the investigation of questions concerning the space-time and energy laws of the solar-diurnal and semidiurnal variations and their dependence on the solar activity in the period 1957 - 1965.

Considering that the theoretical side of this question was elucidated in reasonable detail in the books [1, 2], we investigated only the latest theoretical works and we conducted an analysis of the experimental data. This makes it possible to develop a number of laws of solar-diurnal and semidiurnal variations and, on the basis of them, to select or develop the hypothesis which most completely satisfies the experimental data. /5

CHAPTER I

STATE OF THE PROBLEM OF SOLAR-DIURNAL VARIATIONS BEFORE THE BEGINNING OF THE IGY

1. Amplitude-Phase Characteristics

The first data concerning the fact that the intensity of cosmic rays /6* undergoes variations which are connected with solar time were presented in the works of F. Lindholm [3]. He found that the amplitude of the solar-diurnal variation was $\sim 0.5\%$ and the phase occurs in the afternoon.

The first study, where the results of many years of recordings of four ionization chambers established at various points of the earth were generalized, showed that regular solar-diurnal variations are observed in the intensity of the hard component of cosmic rays [3]. It was found that the diurnal variations at these stations repeated one another and had an amplitude around 0.15%, the maximum coming in the afternoon at approximately 15 hours. The time of the maximum at the equatorial station comes 2 - 3 hours earlier than at the other stations, and the amplitude was the same as that at middle latitude stations. The amplitude of the solar-diurnal variation according to the data of the high-latitude station was the least. The indicated results were obtained on the basis of recording data of the intensity of cosmic rays during the period 1936 - 1952.

*Numbers in the margin indicate pagination in the original foreign text.

In 1952 Ye. S. Glokova, having processed the data of the continuous recording of the hard component of cosmic rays during the period from 1937 through 1946 for the stations Huancayo, Cheltenham, Christchurch and Godhaven, arrived at the conclusion that the amplitude of the diurnal variations increases with an increase in solar activity. The time of the maximum of the diurnal variation from 1937 through 1946 shifted by 1.5 - 2 hours to a later time [4]. Similar results using this same experimental material were obtained by Sarabhai, et al. [6].

Independent of Ye. S. Glokova [6a], D. Vensatesan and A. Dattner [7] established a clear correlation between the amplitude of the diurnal variation and the indexes K and C which characterized the degree of magnetic disturbance, and they showed that it is stronger than the correlation with the sunspot number.

In [8], on the basis of measurements of a long duration of the solar-diurnal variations of the hard component during the period 1953 - 1956, it was shown that these changes are completely the same for both hemispheres of the Earth.

In 1953, H. Elliot and T. Thambyaphillai [9], based on the data of the continuous recording of the hard component at Huancayo, Cheltenham, Christchurch, Manchester and Stockholm, established that the time of the maximum of the diurnal variation at these stations from 1933 through 1942 gradually shifted to a later time, and from 1942 through 1952 a reverse shift took place to earlier hours. This shift had a global character. The authors expressed the supposition that the phase of the diurnal wave varies with a period corresponding to two 11-year cycles. In the work of A. E. Sandstrom [10], based on the data from directional telescopes, it was shown that this shift /6 of the time of the maximum does not depend on the zenith angle and azimuth angle of the cosmic radiation.

In [11,12] the data of the continuous recording of the intensity of cosmic radiation at three stations of USSR were used. The

mean annual vectors at all stations showed a shift of the time of the maximum to earlier hours up to the summer of 1954, following a regular pattern, and then the direction of the change was reversed. The moment of change in direction of the shift of the time of the maximum of the diurnal wave corresponded to the minimum of the solar activity in the solar cycle. By using the data in [13], the direction to the source of the anisotropy was determined. It was found that each 11-year cycle of solar activity is characterized by a specific direction of the phase shift of the diurnal variation of the intensity of cosmic rays. The alteration of the direction of the phase shift coincides with the minimum solar activity. However, this phase shift in different periods of the minimum was uneven. Thus, in 1954 the phase shift was almost 108° relative to the direction in the period 1938 - 1946. In the minimum of 1944 the shift was only 20 - 30°; in 1933 it was around 50°. Thus, the authors of [13] found that the time of the maximum of the diurnal variations of the cosmic rays is clearly correlated with solar activity.

The sharp change in diurnal variation of the cosmic rays in the period of minimum solar activity in 1954 was studied by many authors [7, 14-17]. According to their works, the largest shift of the maximum of the diurnal variation took place in the period of the deepest minimum of solar activity — in June-July, 1954. The time of the maximum shifted to 6-7 hours.

In [18], valuable data concerning the change in direction of the anisotrophy of the diurnal variations in the period of the minimum of 1954 are presented. In the reference, neutron component data obtained at a number of points of the earth during the period 1951 - 1958 were used. The authors noticed that the times of the maximum from 1956 through 1958 were almost constant. From July through September, 1954 the time of the maximum abruptly changed. Thus, in January - March, 1954 the time of the maximum was 13 hours 15 minutes; in July - September, 1954 it was 23 hours; in November, 1954 - February, 1955 it was 12 hours. Using the method in [1], in [18] the angles χ between the axis of the anisotropy and the

earth - sun line in the plane of the ecliptic were determined for various periods. It was shown that in July - September the angle χ varied from 70° (in Standard Time) to 130°, and then the reverse process gradually took place, and already in November - February, 1955, the angle χ reached its former values. The authors attempted to explain the large change in the direction of the anisotropy in the period of the minimum by a shift in the direction of the sunspot field. When doing this, there is difficulty in explaining the regression of the direction of the anistropy in 1955 to the former value.

In [5] the interesting presence of two components (day and night) of the diurnal variations and their change with the solar activity was detected. Based on the data obtained from observations of the hard component of cosmic rays during the period 1937 - 1952 the diurnal wave with a maximum around mid-day (in 1939 - 1946) in later years was changed by the addition of a nighttime component, and in 1948 it manifested itself as a double hump. Then the contribution of the daytime component decreased and the nighttime component increased, and by 1952, only the nighttime wave remained. The semidiurnal variation also changed: in 1946 - 1947 it was a maximum, and in 1952 it was a minimum. The time of the maximum also changed systematically.

Ye. S. Glokova in [19, 20] studied this phenomenon in more detail. An anomalous behavior of the solar-diurnal variation in the minimum of the solar activity was investigated on the basis of the data of ten stations for neutron monitors, a telescope and ionization chambers. From the change of the mean annual moving vector of the solar-diurnal wave on a harmonic diagram, it is seen that the change in amplitude and phase at all stations had a global character. With approach to the minimum of solar activity the amplitude decreased, and the time of the maximum shifted to the morning hours. The maximum in 1954 was by far deeper than in 1944. At /7
the moment of the minimum in 1954 the amplitude of the mean annual diurnal variation of the neutron component decreased almost to zero, whereas in the hard component the amplitude was reduced relative to the maximum of solar activity, but it still remained substantial. During the time of the high solar activity, the amplitude of the diurnal variation in the

neutron component was several times larger than in the hard component. Ye. S. Glokova proposed that the regularly observed solar-diurnal variation in the hard component of the cosmic rays be represented as the sum of two vectors, one of which remains constant and the amplitude of the other decreases with a decrease in solar activity. In this way, Ye. S. Glokova came to the conclusion that the change in amplitude and phase of the observed mean annual vector of the diurnal wave of the hard component of the cosmic rays around the minimum of solar activity is a consequence of the change in the magnitude of the anisotropy beyond the limits of the geomagnetic field.

In [16], when studying the diurnal variation for the east and the west, it was also shown that the shape of the diurnal variations from 1954 - 1955 through 1957 - 1958 changed sharply. In this reference it was pointed out that in 1954 - 1955 there were two maximums: one early in the morning and another around noon; in 1957 - 1958 only one maximum around noon was observed. The mid-day maximum, both in 1958 and in 1954, was observed at approximately the same time, but with an increased amplitude. The time of the maximum of the diurnal variations shifted to earlier hours for all three directions during the period from 1954 - 1955 to 1957 - 1958. U. R. Rao and V. Sarabhai also came to the conclusion that the diurnal variations averaged over one or two years can basically be attributed to an external anisotropy. In 1957 - 1958 this anisotropy was directed at an angle of 73 $\pm$ 4° to the left relative to the earth - sun line. In [15] it was also noted that in 1954-1955 the diurnal variations for the east and the west had large semidiurnal variations and, therefore, the location of the source of the anitropy was indeterminate.

Unusual results were obtained in 1954 - 1955 also on the basis of data of crossed telescopes in a northern direction and a southern direction at Yakutsk at level of 60 m.w.e. [21,22]. The authors noted that in the difference curve of south - north for 1954 - 1955, two maximums were observed: at 5 hours and at 20 hours local time. In the period of the maximum of solar activity in 1958 - 1959 the diurnal variation had one maximum in the

afternoon for all directions. The relationship of the phases between the diurnal variation in the northern direction and the southern direction in years of maximum and of minimum solar activity was the opposite. Measurements with a vertical telescope conducted by V. Kh. Regener [23] at Chakaltaya at a depth of 30 m.w.e. in 1953 - 1954 showed similar results. In the work of G. V. Skripin [21], he remarked that in years of a minimum of activity corpuscular streams, with a direction of the magnetic field toward the Sun, predominated. It seems to us that this assumption is invalid, since such a field would be able only to shift the position of the source of the anisotropy in the plane of the ecliptic, but this is insufficient for the purpose of explaining the anomalous behavior of the solar-diurnal variation of the different directions north - south, east - west.

The anomalous behavior of the solar-diurnal variation of cosmic rays in a minimum of the solar activity possibly is connected with the appearance on the earth in this period of an extrasolar anisotropy of the flux of particles with a direction from the center of the Galaxy — the so-called sidereal-diurnal variation. The flux of cosmic rays in the first approximation is constant in time and isotropic in space. However, the effect of rotation of the Galaxy leads to an anisotropic distribution of the radiation and, consequently, also to a variation in intensity as a function of the sidereal time. The sidereal-diurnal variation may also be connected with the nonuniform distribution of sources of cosmic rays and with the diffusion of particles from the Galaxy which may lead to a specific predominating flux of particles in a certain direction. At the solar activity maximum /8 interplanetary space is filled by magnetic clouds which diffuse particles with an energy of several tens of BeV. Therefore, it is very difficult to detect the sidereal-diurnal variation at the solar activity maximum based on observations of the hard component and the neutron component. At the minimum of the solar activity when the interplanetary space is free of magnetic clouds and the diffusion of cosmic rays is reduced, it is possible to detect the sidereal-diurnal variation.

In [16] the authors describe the anomalous behavior of the vector of the diurnal variation in the period 1954 based on the data of

neutron monitors. They determined that in 1953 and 1955 the time of the maximum of the diurnal variation was constant, whereas in 1954, the vector of the diurnal variation rotated counterclockwise on a harmonic diagram: in the neutron component at the station Huancayo the vector described a complete revolution, at the other stations only a substantial phase shift was observed. A. M. Conforto and J. A. Simpson connected this phenomenon with the disappearance of the solar-diurnal wave in this period and the appearance of a significant sidereal-diurnal variation.

In the maximum of the solar activity the "East" outstrips the "West", and the "North" outstrips the "South", and in the minimum of the solar activity the opposite is true [17, 24, 25].

From 1948 through 1954, M. Possener and J. J. Heerden [17] by means of unshielded counter telescopes conducted measurements of the solar-diurnal variation in the northern direction and southern direction at an angle of 45° to the zenith. During this period, the amplitude of the diurnal variation gradually decreased. During several summer months of 1953 - 1954, the variation showed an anomalous change of phase and the time of the maximum occurred in the night hours. The difference in the phase of the variations for the northern direction and the southern direction during this period decreased.

H. Elliot and D. Rothwell [24] conducted measurements of the solar-diurnal variation in the western direction and the southern direction by means of counter telescopes positioned at an angle of 45° to the vertical during the period from May, 1954, through April, 1955. During this time, the diurnal variations from the east and the west showed a similar time of the maximum, and the amplitude of the variations from the east was significantly smaller than from the west.

Analyzing the result obtained, H. Elliot and D. Rothwell arrived at the conclusion that it is impossible to combine it with the assumption that the diurnal variations are produced by particles with an energy of 20 - 40 BeV,

and that the direction of the anisotropy lies in the plane of the ecliptic or in the vicinity of it. In the opinion of the authors even if one assumes that the energy of the particles which produce these diurnal variations sharply decreases in years of the minimum, then one would succeed only in explaining the coincidence of the phases for the east and the west, but not the substantial difference in the amplitudes of the east and the west. H. Elliot, D. Rothwell and others came to the conclusion that it is impossible to combine all these data with the assumption that the diurnal variations are caused by the anisotropy of cosmic rays outside the range of the earth's magnetic field. They proposed that at least in the period of a minimum of solar activity the solar-diurnal variations are caused by the anisotropic modulation of cosmic rays in the vicinity of the Earth.

A similar result was obtained in [26]. Thus, we see a number of contradictory facts which, as it turns out, may not be explained by a single theory.

L. I. Dorman and O. I. Inozemtseva [27] to a significant degree succeeded in overcoming these difficulties. We will discuss the analysis of this question in the future, but now let us briefly dwell on the question concerning the 27-day change in the amplitude of the diurnal variation in the intensity of cosmic rays.

2. Change of the Anisotropy with a 27-Day Period

The authors of [28,29] showed that a 27-day recurrence period exists in the diurnal variation of cosmic rays. The authors of [28] attempted to relate this phenomenon partially with the 27-day recurrence period of magnetic storms produced by the corpuscular streams which are ejected /9 by the active solar regions over a comparatively long time. An analysis was performed of the data of the continuous recording of the hard component at the station Huancayo during 1936 - 1946. In the work it was found that the 27-day recurrence period of the diurnal variations is most vividly expressed

in the maximum of the solar activity and has a high correlation with the sunspot number.

M. Kodama [30] noticed that the correlation between the 27-day recurrence period of the diurnal variations and solar activity is always negative. Near the minimum of the solar activity an observable 27-day recurrence period of the diurnal variation is not detected.

In [14], A. M. Kuz'min and G. V. Skripin detected a tendency toward a 27-day recurrence period of the diurnal variation both in years of a decrease in solar activity (1951) and also in years of the minimum (1953 - 1954). The best correlation was indicated with the sunspot number, but in connection with this a noticeable coupling with the magnetic activity (the influence of the temperature effect was taken into account) was not detected.

In [31, 32], it was shown that an optimum tendency toward a 27-day recurrence period of the diurnal variation occurs for the moments of time with maximum values of the intensity, whereas for periods with minimum values, it is almost not detected. The authors explained this by the fact that the minimum values of the intensity basically are connected with the Forbush decreases, which substantially weaken the tendency towards recurrence.

In [33], the solar-diurnal variation in intensity of cosmic rays, recorded by means of vertical telescopes at Akhmadabad, was studied. Based on the results of the observations during 1956, it was shown that the 27-day recurrence period of diurnal variations manifests itself distinctly for variations having only one maximum near noon.

3. Semidiurnal Variations

Let us investigate the data on semidiurnal variations. With a harmonic analysis of the experimentally observed solar-diurnal variation of the intensity of the cosmic rays usually two main components are found with

a diurnal period (24 hours) and a semidiurnal period (12 hours). Certain investigators [34 - 37] detected already in early works the existence of a variation with a semidiurnal period. The magnitude of the semidiurnal variation is small. Therefore, in order to obtain reliable results, a high statistical precision of the material being studied is needed. In order to achieve this it is necessary to carry out an averaging of the data of the observations over long intervals of time. The results of [34], which were obtained on the basis of three years of observations at sea level, were reliable. Also, the work of [35], the author of which used two independent ionization chambers installed on the bottom of Lake Constance (at a depth of 40 m), was reliable. The data obtained from each chamber showed the same variation. The amplitude of the semidiurnal variation was found in the interval 0.14 - 0.18% with the time of the maximum at 10 - 11 hours. Based on the data of [34], the amplitude was 0.18%, and the time of the maximum was 3 hours 12 minutes. The semidiurnal variations at the great depth at which they were observed in [35] cannot be correlated with the magnetic field, since the observed particles had large energies. In [35 - 37] the authors, independent of one another, arrived at the conclusion that the semidiurnal variation may be caused by atmospheric fluctuations, the theory of which was developed in [38]. P. Nicolson and V. Sarabhai in [39], performing a quantative evaluation, rejected the conclusion concerning the meteorological origin of the semidiurnal variations. This conclusion was confirmed by the results of [40] based on the data of observations by means of crossed telescopes. The authors showed that a noticeable difference between the northern direction and the southern direction exists for the semidiurnal variation. The second harmonics for the northern and southern directions reach a maximum value at 3 hours 30 minutes, and /10 they are not found in opposite phase with the pressure vector, the maximum of which arrives at 10 hours 30 minutes. The difference between the second harmonics for the northern and southern directions is four times larger than the standard measurement error. This is additional confirmation of the fact that it is impossible to explain the presence of the second harmonics only by atmospheric fluctuations.

It is necessary to note the point of view of J. Katzman and D. Venkatesan [41], who attempted to show the atmospheric origin of the semidiurnal variations. G. V. Skripin and A. I. Kuz'min, repeating the work of [41], also established in [42] that there is a close connection between the phases of the mean monthly semidiurnal fluctuations of the meson intensity of cosmic rays and the barometric pressure. They also came to the conclusion that the semidiurnal variations have an atmospheric origin.

In [11], based on the data of the station Huancayo during the period 1937 - 1944, a harmonic analysis was conducted for 25 effective magnetic storms. This analysis showed that a systematic change of the second harmonic is connected with magnetic storms — an increase in amplitude and a shift of the time of the maximum to the morning hours. This attests to the fact that at least part of the semidiurnal variation of cosmic rays does not have an atmospheric origin. /11

CHAPTER II

SOLAR-DIURNAL AND SEMIDIURNAL VARIATIONS BASED ON THE MATERIAL OF THE IGY - IGC - IQSY

1. Selection of Data and Method of Processing

Considering that the intensity of the hard component of cosmic rays to a strong extent is subjected to the temperature effect, which it is very difficult to take into account accurately and with sufficient reliability [1], we will conduct an analysis of the data of the global network of stations recording the neutron component. Use of only the neutron component was dictated by the fact that it is barely influenced by the temperature, and is easily corrected for the variation in atmospheric pressure. The name of the stations, their coordinates, and elevation above sea level are presented in Table 1.

In the period of maximum solar activity, interplanetary space is strongly disturbed, and effective modulation of the intensity of the galactic cosmic rays is observed. Therefore, for the analysis, relatively quiet periods when the Forbush effects and magnetic storms were not observed on the Earth were separately selected. Nevertheless, the solar-diurnal and semidiurnal variations, even at this time, have amplitudes which are comparatively large and sharply varying in time; the phases of these harmonics also vary sharply in time. Therefore, in the period of a solar activity maximum, for the purpose of clarifying these changes, it is necessary to carry out an analysis of the anisotropy of the cosmic rays based on data averaged over short time intervals. With averaging over long time intervals, it is possible to

TABLE 1. THE NETWORK OF STATIONS, THE DATA FROM WHICH WAS USED IN THIS WORK

Stations	Geographic coordinates		Geomagnetic coordinates		Elevation above sea level, m	Cutoff rigidity R, BeV	
	Lat.	Long.	Lat.	Long.		Quenby-Wenk	Quenby-Weber
Thule	76°33'N	68°50'W	88,0°	1,1°	y. м.*	0,0	0,0
B. Heiss	80 37	58 03E	70,9	156,5	20	0,1	0,1
Resolute	74 41	94 54W	82,9	289,3	17	0,0	0,0
Churchill	58 45	94 05	69,7	322,9	39	0,2	0,1
Mawson	67 36S	62 53E	—73,1	103,8	y. м.	0,1	0,6
Murmansk	63 38N	33 16E	64,0	126,6	» »	0,5	0,5
Murchison	80 03S	18 15E	72,2	137,2	» »	0,1	0,1
Coolidge	64 51N	147 50W	64,7	256,5	» »	0,4	0,5
Deep River	46 06	70 30	57,5	358,0	145	1,0	0,9
Ottawa	45 24	75 54	56,8	351,1	101	1,1	1,0
Washington	44 20	71 40	55,6	356	1917	1,2	1,2
Sulphur	51 12	115 36	58,2	300,3	2283	1,2	0,9
Upsala	59 51	17 35E	58,6	106,0	y. м.	1,3	1,2
Yakutsk	62 01	129 43	51,0	193,8	105	1,5	1,2
Wellington	42 55S	147 14	—51,5	224,5	725	1,9	1,7
London	51 32N	0 06	54,3	83,0	y. м.	2,6	2,2
Chicago	41 50	87 40W	52,6	336,8	» »	1,9	1,5
Lincoln	40 49	96 41	50,8	326,2	350	2,3	2,0
Leeds	53 49	1 33	56,3	83,0	100	2,1	1,7
Amsterdam	52 30	04 36E	54,2	89,2	y. м.	2,5	2,1
Kiel	54 20	10 08			» »	2,3	1,9
Herstmonseux	50 52	0 20	53,5	83,8	23	2,3	2,3
Gottingen	51 31	9 56	52,3	93,7	273	3,0	2,4
Climax	39 22	106 11W	48,1	315,5	3400	3,1	2,8
Weisenau	47 48	9 30E	49,0	91.5	427	4,2	3,2
Zugspitze	47 25	10 59	48,2	92,4	2960	4,2	3,3
Munich	48 12	11 36			y. м.	4,2	3,3
Jungfrau-Joch	46 33	7 59	47,9	89,5	3450	4,4	3,4
Rome	41 54	12 31	42,5	92,0	66	6,3	5,0
Alma-Ata	43 15	76 55	33,0	150,8	806	6,3	5,5
Norikura	36 07	137 33	25,6	203,6	2770	11,9	9,1
Buenos Aires	34 36S	48 30W	—23,3	9,3	y. м.	11,4	10,6
Rio de Janeiro	22 54	43 14	—12,7	24	» »	12,1	11,5
Mina Aguilar	23 12	65 42	—11,7	3,1	4000	12,6	12,5
Machapu	21 18N	157 39	21,3	267,0	y. м.	13,5	11,0
Ahmadabad	23 01	72 36	13,9	143,9	» »	15,8	14,6
Huancayo	12 02S	75 20	— 0,6	353,8	3400	13,7	14,2
Kampala	0 20N	32 34E	— 2,0	101,4	1196	15,3	14,5
Guadalcanal	10 14	77 28	0,6	147,1	2343	17,5	17,6
Lae	6 44S	147	—16,0	217,4	y. м.	15,8	14,9
Dallas	32 47N	96 48W					

*Translator's note: y.m. designates sea level

" " Commas indicate decimal points.

lose information concerning the changes in short-period variations. But with averaging over short time intervals the data have too large an error; therefore, one is obliged to carry out the averaging for a month. In order to decrease the statistical errors, the data averaging was carried out for groups of stations. All the stations were divided into zones with mean cutoff energies of g = 1.0, 1.4, 2.2, 3.2, 6.0, 11.1, and 15.3 BeV. The values of the cutoff energies were selected in accordance with [43] with consideration of the correction for the nondipolarity of the earth's magnetic field.

For the purpose of finding the amplitudes and phases of the solar-diurnal and semidiurnal variations, a harmonic analysis and the calculation of the first and second harmonics were carried out.

2. Amplitudes of the Solar-Diurnal Variations and Their Correlation with Solar and Geomagnetic Activity

It is advisable to begin the studies in 1958, which was a year of maximum solar activity (it is important to consider also that all equipment for recording the neutron component of cosmic rays in the global network of stations for the IGY were basically set up and operated at this time). /12

The values of the amplitudes of the first harmonic of the diurnal variations are presented in Figure 1. The amplitude is plotted along the ordinate axis, and the cutoff energy is plotted along the abscissa axis. The numerical values of the amplitude of the first harmonic of the diurnal variations averaged over latitude zones are presented in Table 2. Since in March there were strong disturbances of the earth's magnetic field and also because of the Forbush effects, this month was omitted. /13

From Figure 1 and also from Table 2 it is seen that the dependence of the amplitude on the cutoff energy changes rather sharply with time. Nevertheless, the following general law of the behavior appears for all periods: the first harmonic in the region of high latitudes has an amplitude of 0.25%,

TABLE 2. AMPLITUDE OF THE FIRST HARMONIC r_1 in %

Months	Cutoff energy g in BeV						
	1.0	1.42	2.15	3.2	5.0	11.09	15.26
Jan.	0.12±0.03	0.24±0.02	0.29±0.02	0.38±0.02	0.39±0.02	0.17±0.02	0.44±0.04
Feb.	0.16±0.04	0.22±0.03	0.40±0.03	0.34±0.02	0.41±0.03	0.32±0.02	0.32±0.05
Apr.	0.20±0.05	0.30±0.03	0.24±0.03	0.29±0.03	0.47±0.04	0.29±0.03	0.44±0.05
May	0.27±0.04	0.22±0.02	0.29±0.02	0.28±0.02	0.28±0.03	0.18±0.02	0.38±0.04
June	0.25±0.03	0.32±0.02	0.36±0.02	0.48±0.02	0.36±0.02	0.41±0.02	0.33±0.04
July	0.09±0.03	0.19±0.02	0.33±0.02	0.36±0.01	0.31±0.02	0.27±0.02	0.49±0.03
Aug.	0.19±0.03	0.33±0.02	0.31±0.02	0.37±0.02	0.28±0.02	0.19±0.02	0.26±0.03
Sept.	0.42±0.03	0.45±0.02	0.41±0.02	0.51±0.01	0.34±0.02	0.27±0.02	0.23±0.031
Oct.	0.02±0.03	0.07±0.02	0.21±0.02	0.25±0.01	0.19±0.02	0.12±0.03	0.15±0.03
Nov.	0.08±0.03	0.22±0.02	0.27±0.02	0.38±0.01	0.33±0.02	0.23±0.03	0.06±0.03
Dec.	0.02±0.03	0.27±0.02	0.28±0.02	0.46±0.02	0.37±0.02	0.22±0.03	0.34±0.03

then with an increase in the cutoff energy it increases, reaching a maximum at g = 3-5 BeV, and then in all cases it falls off, reaching a minimum in the region g = 11 BeV. In the region g $\sim$ 11 BeV, in seven of the 11 months the amplitude of the first harmonic slightly increases. In the other four cases, it decreases.

It is interesting to note the increase in the amplitude of the diurnal and semidiurnal vairations in the equatorial region. This phenomenon may indicate that in certain periods a mechanism is in action, directed in the plane of the ecliptic, which is responsible for the nature of the diurnal and semidiurnal variations.

Let us investigate how the amplitude of the diurnal variation changed during 1958 various latitudes, and let us compare these data with the

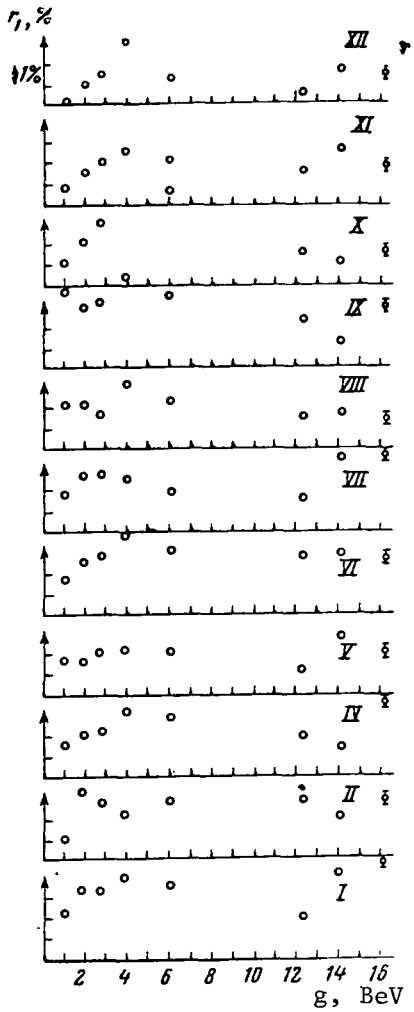

Figure 1. Dependence of the amplitudes of the first harmonic r_1 on the cutoff energy g for various periods of 1958.

change in sunspot number and the K_p index of the magnetic field .

Figure 2 presents the mean-monthly values of the amplitude of the diurnal variations and the mean-monthly values of the sunspot number and the K_p index during 1958-1962; a positive correlation is observed between the sunspot number and the amplitude of the diurnal variation based on the data of high-latitude stations. At the same time, a similar correlation with the K_p index is not observed. At the equatorial stations the opposite picture occurs — a positive correlation is better developed with the K_p index, and there is almost no positive correlation with sunspot number. For a better explanation of the dependence of the amplitude of the diurnal variation on solar and geomagnetic activity, we expressed the behavior of the amplitude of the first harmonic as a function of sunspot number and the K_p index. Therefore, the mean monthly sunspot numbers were plotted along the abscissa in Figure 3, and the values of the amplitudes of the first harmonic in percent were plotted along the ordinate axis. From Figure 3 the clearly expressed correlation of the amplitude of the diurnal variation with sunspot number is distinctly seen for stations with a mean cutoff rigidity of 1 Bev; a

slightly weaker dependence is seen from the data of the station with a mean cutoff rigidity of 1.88 BeV, and a dependence of any kind is completely absent in the stations with a cutoff rigidity of 6.4 BeV and higher.

Let us investigate the dependence of the diurnal variation on the mean-monthly values of the diurnal sum of the K_p index. For this purpose in Figure 4 the values of the K_p index are plotted along the abscissa axis, and the amplitudes of the first harmonic are plotted along the ordinate axis. From Figure 4 it is seen that the correlation of the amplitude of the first harmonic with the K_p index is more clearly expressed at the equatorial stations than at the other stations. Let us note the distinctive feature which is characteristic for the first harmonic calculated on the basis of data from stations located at all latitudes. When the magnetic field is quiet (the sum of the K_p index for a day is $\leqslant 16-17$) a large amplitude of the diurnal variation is observed. Then, with values of the K_p index larger than 20, the amplitude of the first harmonic increases slightly at all latitudes. /14

One may observe the following fact: there is a completely similar change in the amplitude of the diurnal variation in the region where the sum of the K_p index changes from 16 to 18 (data obtained on relatively magnetically quiet days were investigated — that is, when magnetic storms and the Forbush effects were absent, but on the whole the solar and geomagnetic activity were high).

It is interesting to investigate the dependence of the sum of the first and second harmonics on the sunspot number and on the K_p index (Figure 5). In Figure 5 a positive correlation is observed between sunspot number and the sum of the first two harmonics only for the high-latitude stations. For the mid-latitude stations the dependence, if there also is one, is weak (g = 1.88, 2.74, 3.88, 6.4), and for the equatorial stations is not observed at all.

To clarify the correlation between the changes in the amplitudes of the first and second harmonics, Figure 6 presents the values of the amplitude of the first harmonic (the abscissa axis) as a function of the second harmonic (the ordinate axis). From Figure 6 it is seen that at the

high-latitude stations (mean cutoff rigidity of 1.0 BeV) with an increase in the amplitude of the first harmonic there is a decrease in the amplitude of the second harmonic, and this dependence is expressed rather clearly. At the mid-latitude stations a specific dependence is not observed, although there is a certain tendency toward a decrease in the amplitude of the second harmonic with an increase in the first harmonic (1.4, 5.5 BeV). At the equatorial stations, the opposite picture is observed: with an increase in the amplitude of the first harmonic, there is an increase in the amplitude of the second.

The results presented show that there is a high positive correlation of the amplitude of the diurnal variation with sunspot number based on the data of high-latitude stations. At the equatorial stations the same correlation is observed only with the K_p index of the earth's magnetic field. There is a weak correlation between the amplitude of the first and second harmonics based on the data of high-latitude stations and a slightly better correlation based on the data of the mid-latitude and equatorial stations.

In conclusion, let us present the numerical values of the correlation coefficients calculated from the mean monthly data of 1958 between the amplitudes of the first and second harmonic, sunspot number, and the K_p index. The results of the calculations are presented in Table 3. /15

The table shows that a high positive correlation occurs between: 1) the amplitude of the first harmonic and the sunspot number at the high-latitude stations; 2) the amplitude of the first harmonic and the K_p index at the low-latitude stations.

3. Energy Spectrum of Diurnal and Semidiurnal Variations Based on the Data of 1957-1958

The energy spectrum of the diurnal variation in the g region up to 17 BeV was calculated from the latitude dependence by means of the coupling coefficients [1] based on the equation

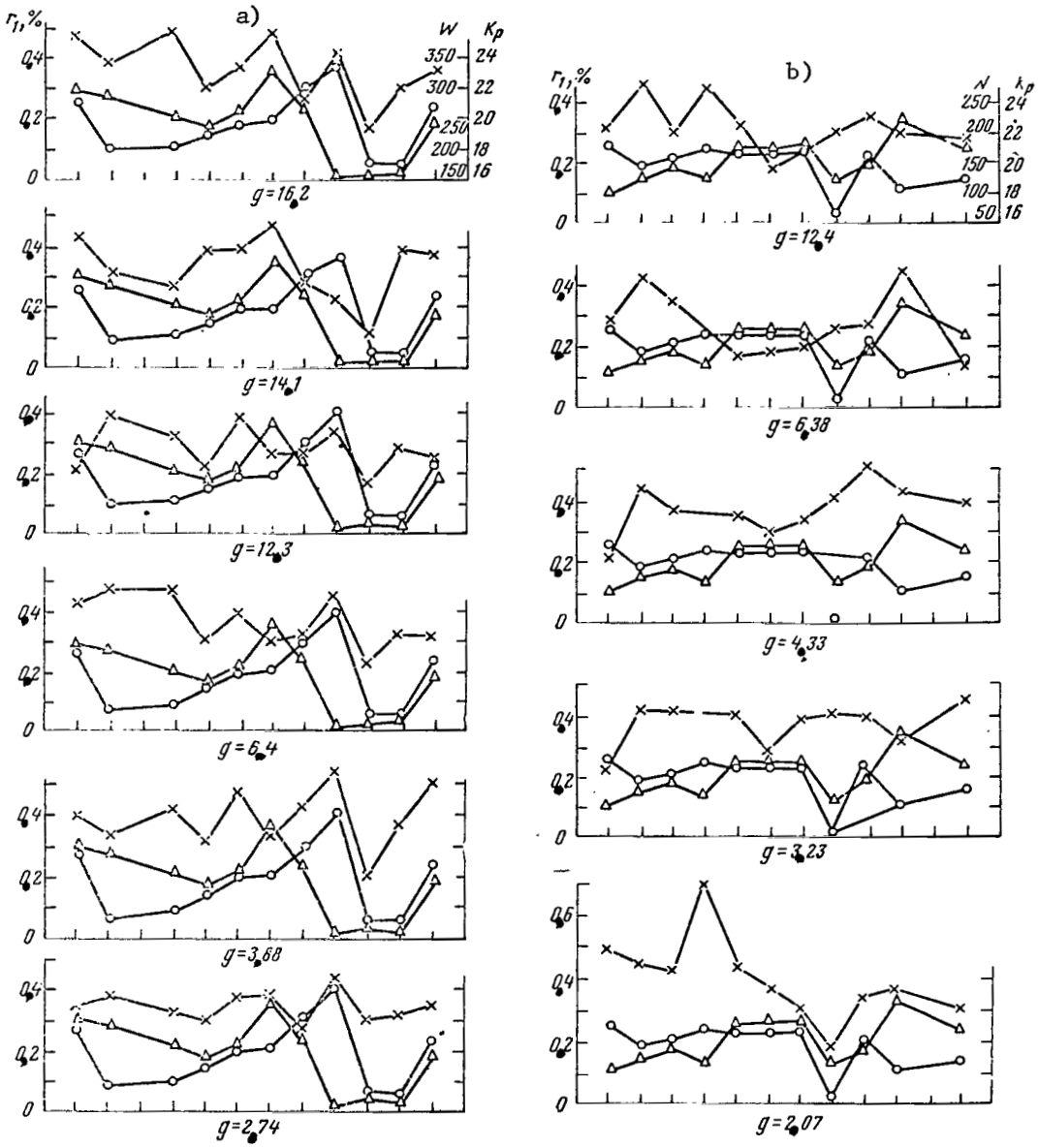

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Figure 2. Change in the amplitude of the first harmonic of the diurnal variation r_1, the sunspot number W and the K_p index of geomagnetic activity in 1958 (a) and in 1960-1962 (b, c, d).

1 - amplitude of the first harmonic r_1 in %;
2 - sunspot number W;
3 - planetary index of geomagnetic activity K_p for various values of the cutoff energy g (in BeV).

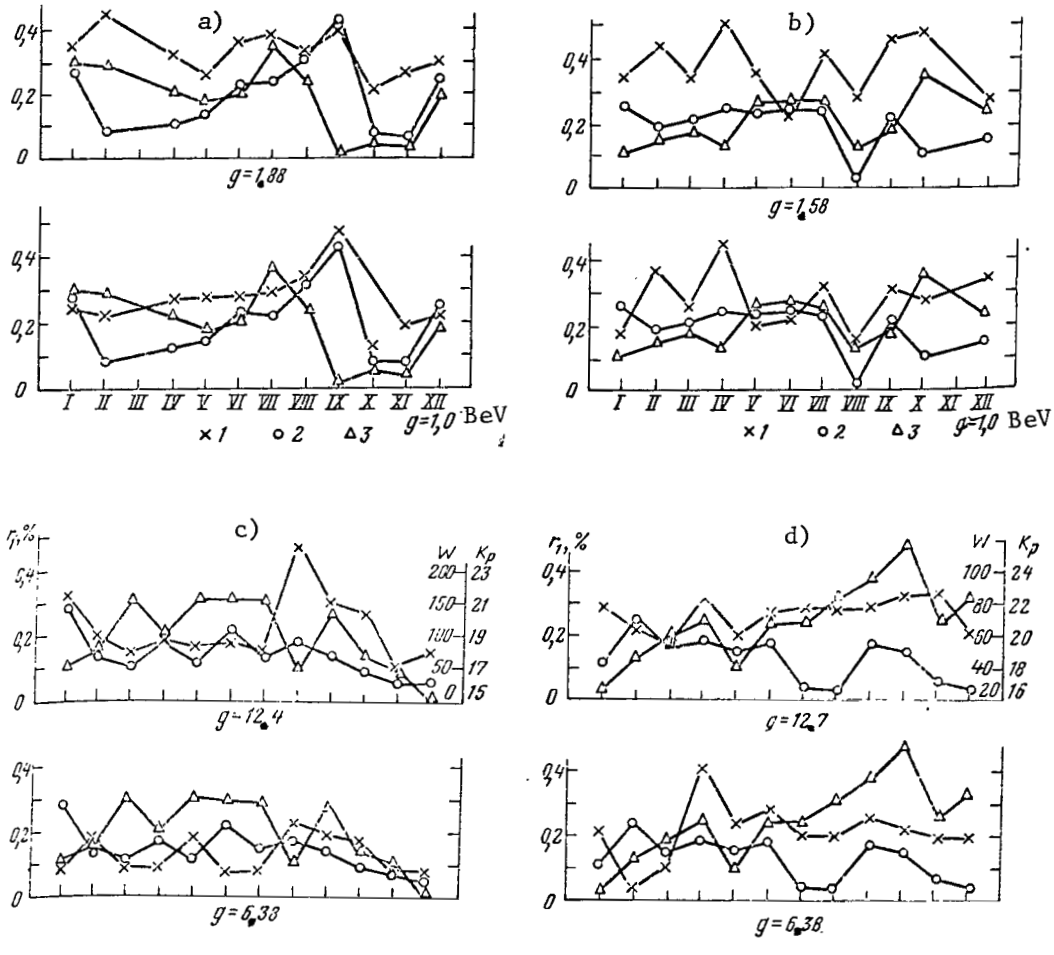


Figure 2. (Continued).

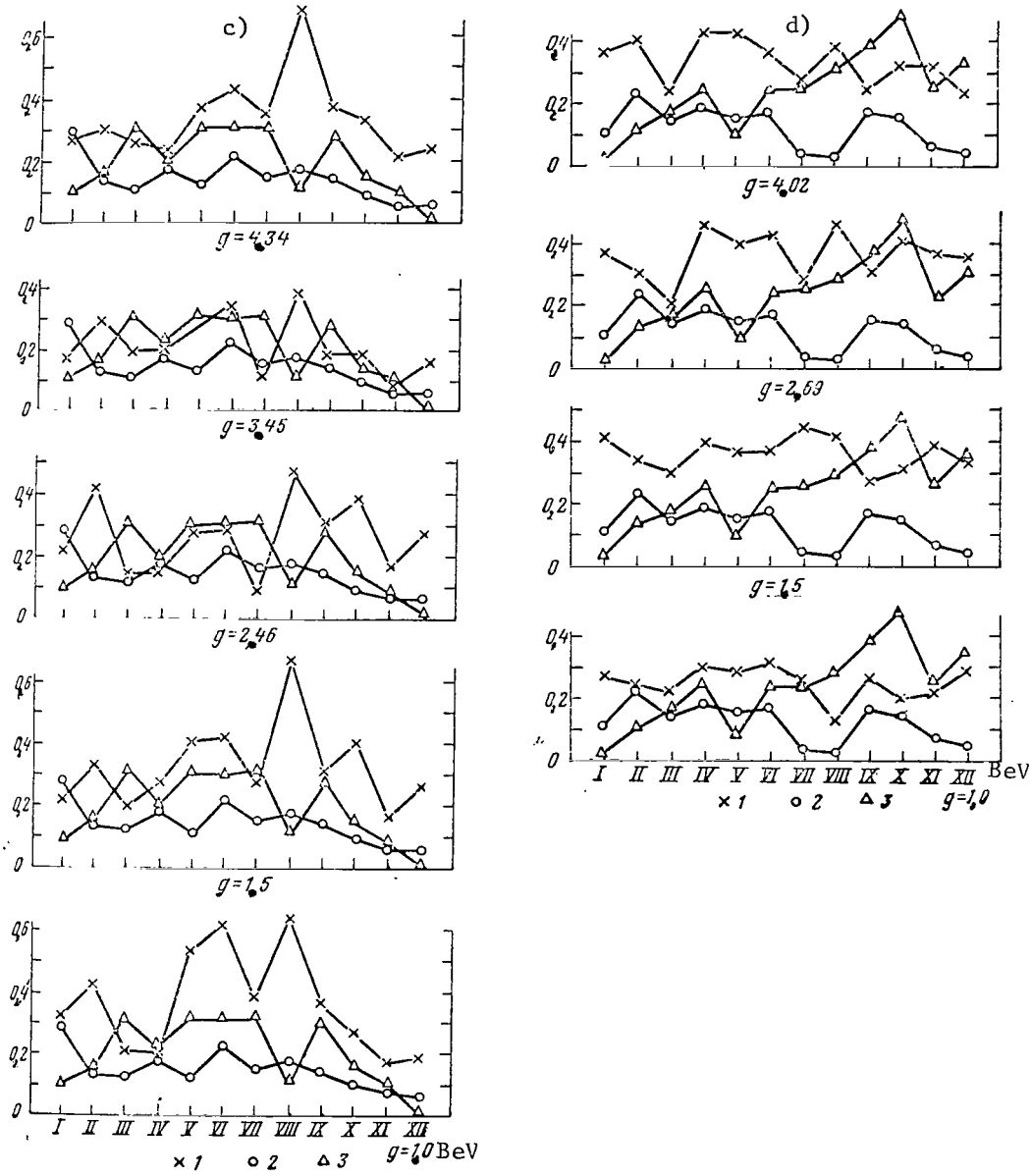


Figure 2. (continued)

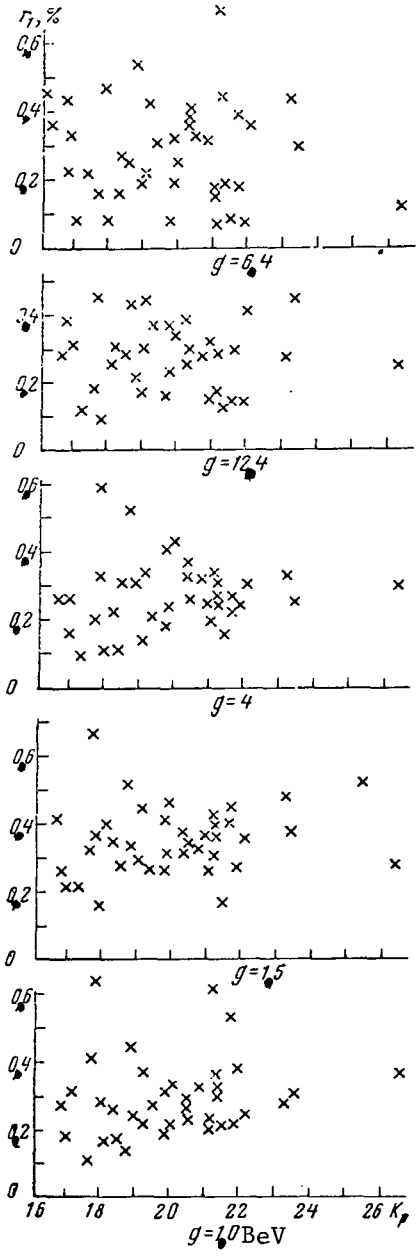


Figure 3. Behavior of the amplitude of the first harmonic r_1 as a function of sunspot number W for various values of the cutoff energy g (in BeV).

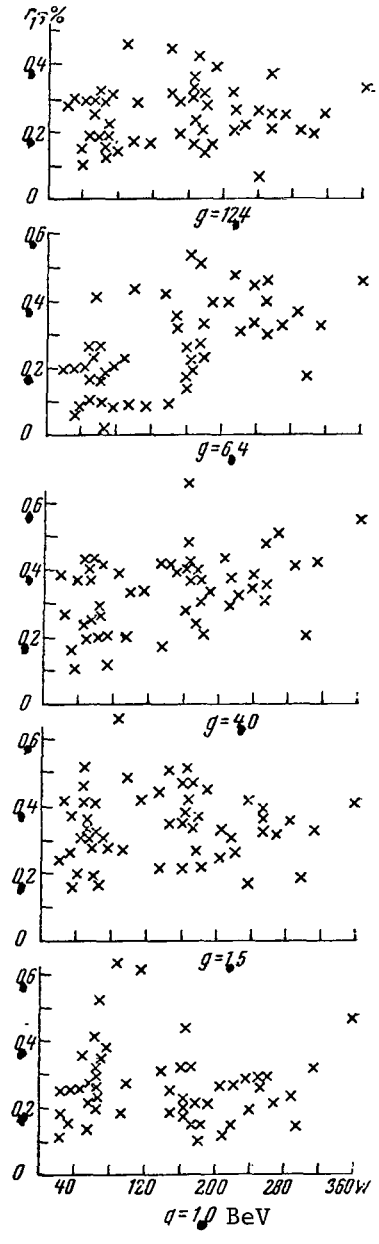


Figure 4. Amplitude of the first harmonic r_1 as a function of the mean monthly values of the diurnal sums of the K_p index for various values of the cutoff energy g (BeV).

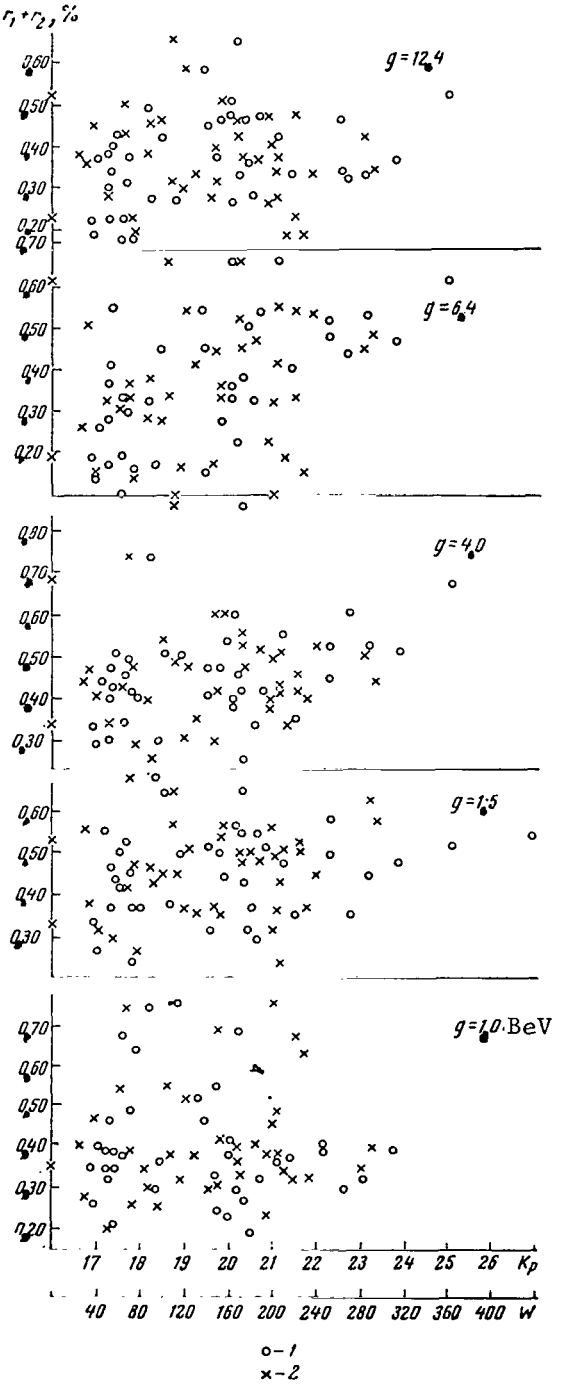


Figure 5. Sum of the amplitude of the first harmonic r_1 and the second harmonic r_2 as a function of sunspot number W(1) and the K_p index (2) for various values of the cutoff energy (in BeV).

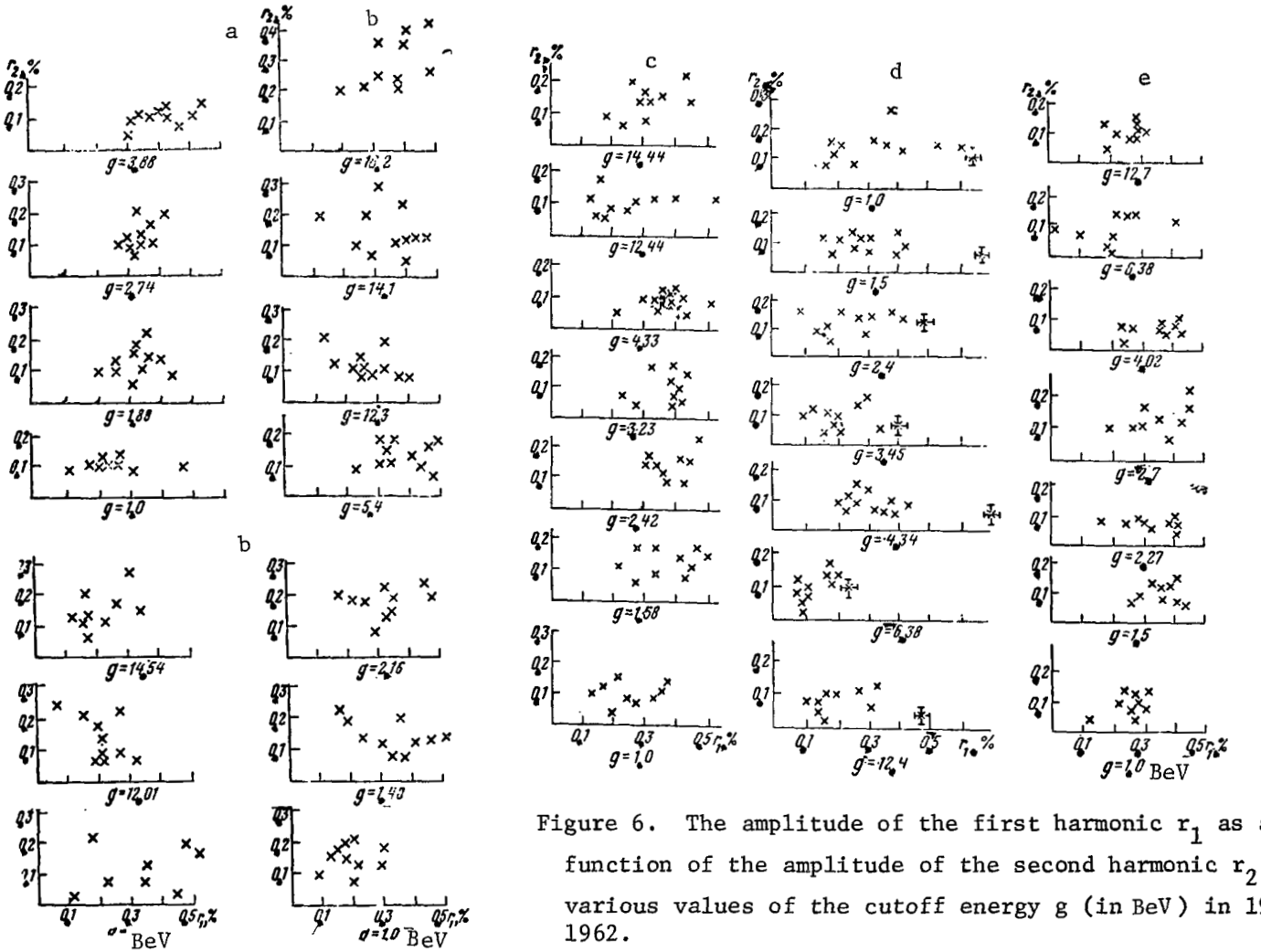


Figure 6. The amplitude of the first harmonic r_1 as a function of the amplitude of the second harmonic r_2 for various values of the cutoff energy g (in BeV) in 1958-1962.

a - 1958; b - 1959; c - 1960; d - 1961; e - 1962

TABLE 3. CORRELATION COEFFICIENTS

Latitude zone with a mean cutoff energy in BeV	Between the amplitudes of the first and second harmonics	Between the amplitude of the first harmonic and sunspot number	Between the amplitude of the first harmonic and the K_p index
1.0	0.12	0.82	−0.07
1.9	0.22	0.61	0.4
2.7	0.52	0.42	0.05
3.9	0.05	0.72	−0.29
6.4	0.08	0.27	0.11
12.3	−0.21	0.07	0.65
14.1	−0.17	0.10	0.94
16.2	0.29	0.24	0.60

$$\frac{\delta D}{D}(\bar{\varepsilon}) = [\delta N_{\lambda,\,k+1} - \delta N_{\lambda,\,k}] \Bigg/ \int_{\varepsilon_{\lambda,\,k}^{\min}}^{\varepsilon_{\lambda,\,k+1}^{\min}} W(\varepsilon,\,h)\,d\varepsilon \cdot N_{\lambda,\,0},$$

where $\varepsilon_{\lambda,k+1}^{\min} < \bar{\varepsilon} < \varepsilon_{\lambda,k}^{\min}$; $W(\varepsilon, h)$ is the coupling coefficient between the primary and secondary fluxes of cosmic rays; D(ε) is the energy spectrum of the disturbed primary flux of cosmic rays.

The spectrum was calculated for each month and also was based on the mean annual data presented in Figure 7. Figure 7 presents the amplitude of the first harmonic during the period 1957-1958 [44] and the mean annual values of the second harmonic. The energy spectrum of the diurnal variation is analytically described by a power function of the form

$$\frac{\delta D}{D}(\varepsilon) = a\varepsilon^{-\gamma}.$$

The values of the exponent for each month of 1958 are presented in Table 4.

It is necessary to point out that, for all those cases when the amplitude of the diurnal variations in the region of the low latitudes increased, we used the data of the stations for which g = 3 - 11 Bev. The lower limit of the spectrum is E $\sim$ 6 BeV.

In Table 4 the values of the exponent (γ') which were obtained when calculating the spectrum are also presented taking into account the latitudinal distribution of the intensity of the diurnal variation source [1].

We calculated the energy spectrum on the basis of a method proposed in [45]. The results of the calculations showed that the spectrum is described by a power function with an exponent which does not differ from the values presented in Table 4. /22

TABLE 4. ANNUAL VARIATION OF THE EXPONENT IN THE SPECTRUM OF THE DIURNAL VARIATION

Exponent	Months										
	Jan	Feb	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
γ	0.47	0.41	0.52	0.30	0.40	0.47	0.52	0.40	0.32	0.57	0.53
γ'	0.62	0.42	0.57	0.56	0.44	0.47	0.61	0.45	0.39	0.54	0.67

In Figure 7 the mean annual values of the amplitude of the first and second harmonics are shown as a function of the cutoff energy g.

One can notice the good agreement of the amplitudes of the first harmonics calculated by us and in [44].

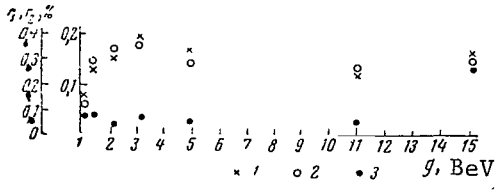


Figure 7. The mean annual values of the amplitudes of the first harmonic r_1 and the second harmonic r_2 as a function of the cutoff energy g during the second half of 1957 and 1958.

1 - amplitude of r_1 based on the data in this paper;
2 - amplitude of r_1 based on the data in [44];
3 - amplitude of r_2 based on the data in this paper.

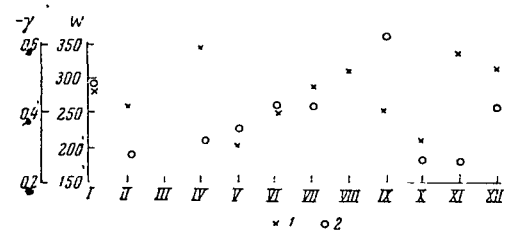


Figure 8. The change in time of the exponent γ (1) in the energy spectrum and sunspot number W (2) during 1958.

It is interesting to investigate the month-to-month changes in the exponent γ in the energy spectrum of the diurnal variation and the sunspot number W in 1958 (Figure 8). From Figure 8 it is seen that there is no clearly expressed law governing the behavior. The correlation coefficient between the spectral exponent γ and the sunspot number W equals 0.56. An analysis of the correlation of γ with the K_p index shows that the correlation coefficient between γ and the K_p index is negative and equals 0.27.

It is rather difficult to calculate the energy spectrum of the semidiurnal variations because of the small magnitude of the amplitude of the second harmonic. Nevertheless, a specific dependence of the semidiurnal variation on cutoff energy is seen. As is seen from the data presented above (Figure 7), starting with g = 9 - 10 BeV, the amplitude of the second harmonic increases and has a maximum at the equator. Considering this relationship (based on data averaged over June - December 1957 and over 1958), the energy spectrum of the semidiurnal variation in the region g $\sim$ 9 - 16 BeV was calculated using the coupling coefficients [1, 2]. The spectrum has a power-law form $\frac{\delta D}{D}(\varepsilon) = a\varepsilon^{\gamma}$ with the positive exponent γ = 0.9.

4. The Phase of the Solar-Diurnal Variation in 1958 and its Correlation with Solar and Geomagnetic Activity /23

Figure 9 illustrates the behavior of the phase of the solar-diurnal variations as a function of the cutoff energy for each month of 1958. Figure 9 shows that, with an increase in cutoff energy the phase of the solar-diurnal variation shifts to earlier hours. Accordingly, the difference between the time of the solar variation maximum between the high-latitude and equatorial stations in various months varies very greatly, and ranges from 1.7 to 8.4 hours. The numerical value of the time of the maximum is given in Table 5. From Table 5 and from Figure 9 it is seen that the scatter of the phase in the high-latitude region falls basically between 1500 and 1600 hours, and in the low-latitude region it varies from 0800 to 1400 hours.

TABLE 5. TIME OF THE MAXIMUM OF THE DIURNAL VARIATION BASED ON THE DATA OF 1958

Months	Cutoff energy g in BeV						
	1,0	1,42	2,15	3,2	5,0	11,09	15.26
January. . .	16,6	15,7	14,7	14,9	14,0	13,9	13,6
February . .	14,9	13,7	13,8	14,3	12,4	12,7	11,1
April . . .	19,5	15,2	14,2	14,5	15,3	13,6	13,5
May	16,6	13,8	13,3	13,0	12,0	9,9	11,8
June	15,2	16,0	15,7	14,7	13,5	13,1	13,5
July	14,9	13,6	12,7	12,3	9,6	10,2	10,4
August . . .	16,2	15,2	15,6	14,5	13,2	13,4	12,8
September .	15,6	14,8	15,8	15,0	13,1	13,1	11,5
October . .	14,2	10,5	14,2	13,6	11,1	10,6	11,5
November. .	16,2	14,9	13,8	13,1	12,5	11,1	7,8
December. .	15,0	14,9	14,5	14,3	14,3	12,1	11,3

*Translator's Note: Commas should be changed to decimal points.

It is necessary to investigate the behavior of the phase of the first harmonic as a function of sunspot number and the K_p index of the earth's magnetic field. For this purpose, we calculated the correlation coefficient between the phase of the first harmonic and the sunspot number /24

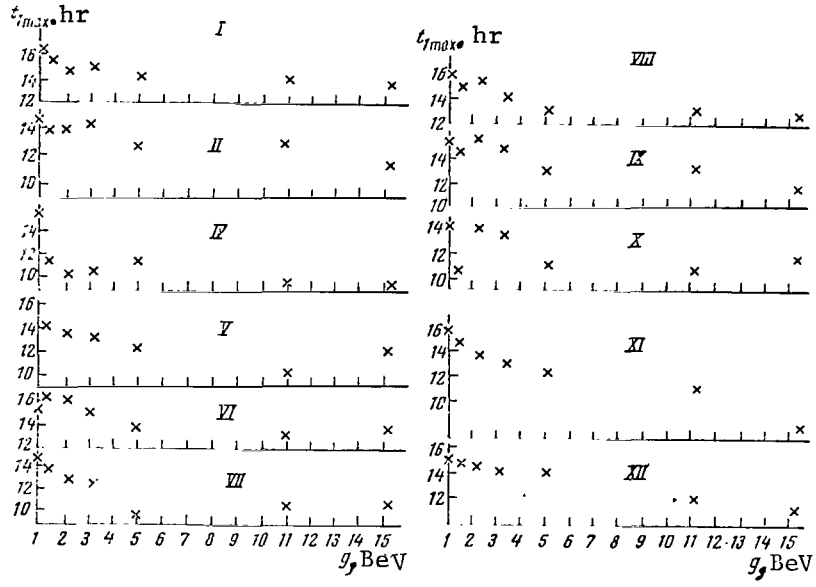


Figure 9. Phase of diurnal variations as a function of the cutoff energy g based on the data of 1958.

and also the K_p index for each latitudinal zone. The results of the calculations are presented in Table 6.

Table 6 shows that the correlation coefficient between the sunspot number and the phase of the first harmonic for all latitudes is positive and has values from 0.09 to 0.67 — that is, with an increase in the sunspot number the time of the maximum is shifted to later hours. However, according to recent concepts concerning diurnal variations, it would appear that an inverse correlation should exist. The correlation coefficient between the K_p index and the phase of the first harmonic for data obtained at high and low latitudes is positive; for the data obtained in the middle latitudes, it is negative. This fact is interesting in that the data for the high and low latitudes (where there is a positive correlation) contradict recent ideas. /25

TABLE 6. CALCULATIONS OF THE CORRELATION COEFFICIENTS

Cutoff energy g in BeV	Between the phase of the first harmonic and sunspot number.	Between the phase of the first harmonic and the K_p index.	Between the phase of the second harmonic and sunspot number	Between the phase of the second harmonic and the K_p index.
1	0.09	0.48	0.16	—0.02
1.88	0.46	0.22	0.13	—0.08
2.74	0.67	—0.29	—0.05	—0.29
3.88	0.49	—0.11	0.34	0.04
6.0	0.24	—0.10	—0.07	—0.58
12.3	0.60	—0.23	0.13	—0.35
15.6	0.36	+0.36	0.06	—0.01

It is known [46-48] that the amplitude of solar-diurnal variations increases primarily during magnetic storms (the K_p index is large) and the time of the maximum is shifted to earlier hours — that is, a negative correlation must be observed at both low and high latitudes.

Let us investigate the change in the second harmonic phase. Table 6 shows that the correlation between the phase of the second harmonic and sunspot number (column 4) and between the phase of the second harmonic and the K_p index (column 5), within the limits of errors, is absent except for the latitudinal zones with a mean cutoff energy of g = 3.88 BeV in the first case, and g = 6.0 and 12.3 BeV in the second case.

At present it is very difficult to explain the observed local behavior of the phases of the first harmonic, since the mechanism of the diurnal variations is still not clearly understood.

In Figure 10 the relationship of the time of the semidiurnal variation maximum is shown as a function of the time of the maximum of solar-diurnal

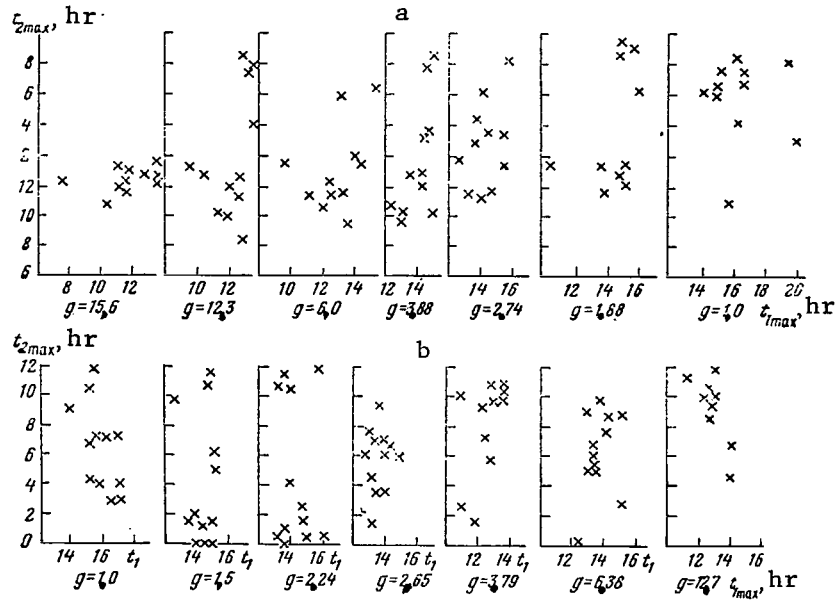


Figure 10. Time of the maximum of the semidiurnal variation as a function of the time of the maximum of solar-diurnal variation for 1958 (a) and 1962 (b) for various energies g (in BeV).

variation. It is seen that at the mid-latitude stations (g = 2.7 - 3.8), when the time of the first harmonic maximum shifts to later hours, the time of the second harmonic maximum changes clockwise — that is, it is displaced on the average from 1000 hours to 1200 hours, from 1200 hours to 0100 hour, etc. At the high-latitude stations (a cutoff energy of 2 BeV or less) such a relationship is not observed. For a clearer representation of the law governing the behavior of the phases of the first and second harmonics, we calculated the correlation coefficients between them for each latitudinal zone. These correlation coefficients are given in Table 7.

Table 7 shows that a noticeable inverse correlation occurs which is beyond the limits of errors only at the mid-latitude and polar

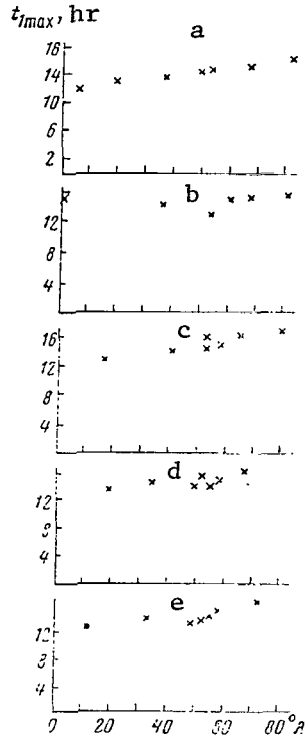


Figure 11. Time of the maximum of the first harmonic as a function of geomagnetic latitude based on the data for 1958-1962 (a-e).

stations. Thus, by considering the data presented in Figure 10 and Table 7, one can say that in the region of maximum sensitivity of the rigidity threshold, with a shift of the time of the first harmonic maximum to later hours, the time of the second harmonic maximum is shifted to earlier hours.

In Figures 11 and 12 the behavior of the time of the first and second harmonic maxima is presented as a function of geomagnetic latitude for mean annual values.

Figure 11 shows that when the latitude increases, the time of the first harmonic maximum is shifted to later hours. The change in the time of the first harmonic maximum is very well described by the equation

$$t_1 = a - b\cos\theta,$$

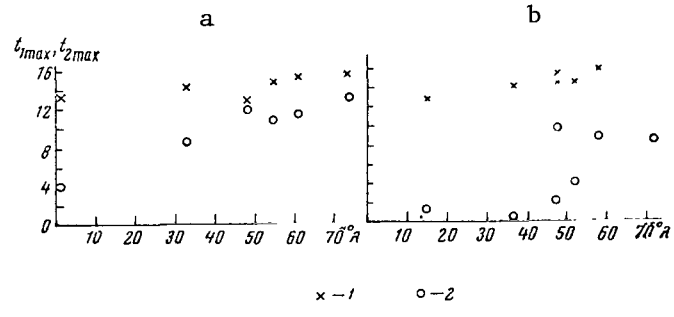


Figure 12. Time of the maximum of the first and second harmonics as a function of geomagnetic latitude during 1959 (a) and 1961 (b).

1 - $t_{1\ max}$ 2 - $t_{2\ max}$

TABLE 7. CORRELATION COEFFICIENTS BETWEEN THE PHASES OF THE FIRST AND SECOND HARMONICS

Mean cutoff energy in BeV	1.0	1.88	2.74	3.88	6.0	12.30	15.60
Correlation coefficient between t_1 and t_2	-0.28	0.17	0.58	0.32	0.14	0.07	-0.13

where θ is geomagnetic latitude; a and b are constant coefficients equal /26
to 16.48 and 3.89, respectively (for 1958). The coefficients a and b vary from month to month as a function of the solar and geomagnetic activity. Below, the correlation coefficients between the geomagnetic latitude and the phases of the first harmonic are presented by months:

Jan	Feb	April	May	June	July	Aug	Sept	Oct	Nov	Dec
0.82	0.53	0.70	0.82	0.49	0.94	0.78	0.89	0.77	0.92	0.90

Let us investigate the behavior of the first harmonic phase as a function of geographic longitude. In order to eliminate the latitudinal variations, we separated all the stations into three groups. In the first group, we placed the stations located at high latitudes; in the second group, the stations located at middle latitudes, and in the third group, the stations at low latitudes.

Then, for each group and for each month of 1958, we calculated the correlation coefficients between the phase of the first harmonic and the geographic longitude. The results of the calculations are presented in Table 8.

TABLE 8. CORRELATION COEFFICIENTS BETWEEN THE PHASE OF THE FIRST HARMONIC AND GEOGRAPHIC LONGITUDE

Groups	Jan	Feb	April	May	June	July	Aug	Sept	Oct	Nov	Dec
High-latitude	-0.10	0.04	0.86	0.11	-0.65	0.77	0.47	-0.04	0.90	0.19	-0.55
Mid-latitude	0.08	-0.09	0.45	0.77	0.46	0.14	0.21	-0.21	-0.19	0.09	0.04
Equatorial	0.66	0.02	-0.01	-0.61	0.08	-0.80	-0.12	-0.18	-0.18	-0.63	-0.41

In [48a], based on the data of the global network of stations recording the neutron component of cosmic rays in the IGY period, an analysis of diurnal variations was made. In Table 9 the names of the stations, the geomagnetic latitude, the time of the maximum and the amplitude of the diurnal variation of cosmic rays are given based on data averaged during the IGY period.

In Figure 13 the behavior of the amplitude and the time of the diurnal variation maximum are presented as a function of geomagnetic latitude. The regression line calculated separately on the basis of $t_{1\ max}$ data for high-mountain stations and for stations located at sea level, and having coordinates between 60° N and 60° S (Figure 13), shows that $t_{1\ max}$ is expressed on the /27 basis of data of the high-mountain stations by

$$t_{1\max} = 12{,}93 + 0{,}03\lambda \pm 0{,}55 \text{ hr}$$

and based on data of the stations at sea level by

$$t_{1\max}(\lambda) = 10{,}12 + 0{,}08\lambda \pm 0{,}37 \text{ hr},$$

respectively, where λ is geomagnetic latitude.

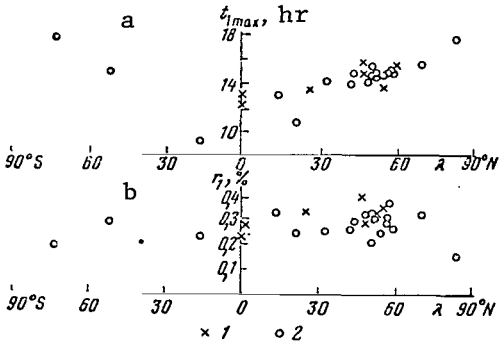


Figure 13. The time of the maximum (a) and the amplitude of the first harmonic (b) as a function of geomagnetic latitude λ

1 - based on the data of high-mountain stations;
2 - based on the data of stations at sea level.

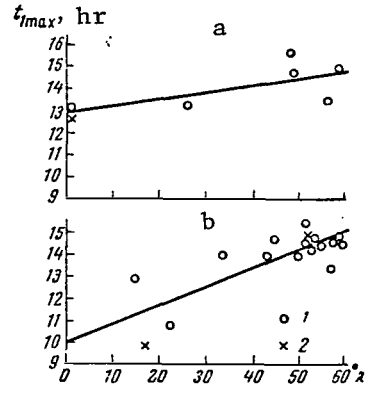


Figure 14. The regression lines t_{max} separately for high-mountain stations (a) and the stations at sea level (b)

1 - based on the data from stations in the northern hemisphere;
2 - based on the data from stations in the southern hemisphere.

From Figure 14 it is seen that at the lower latitudes a difference occurs in $t_{1\ max}$ at sea level and at a high elevation. The authors eliminated from these data the station Hermanus since it is located in a geomagnetic anomaly.

5. Change of the Energy Spectrum of the Solar-Diurnal Anisotropy with the Solar Activity Cycle

Above, we investigated the energy spectrum of the solar-diurnal anistropy calculated on the basis of data on the nucleon component during the period 1957-1958. In [49] the anisotropy energy spectrum was investigated using a complex of surface and underground equipment recording the hard component of the intensity of cosmic rays, during the same approximate period as that in [50, 51]. From [49-51] it is seen that the energy spectrum /28 has a power-law form $\frac{\delta D}{D}(\varepsilon) = a\varepsilon^{-\gamma}$ with the exponent $\gamma \sim 5$. Thus, one may conclude

TABLE 9. TIME OF THE MAXIMUM AND THE AMPLITUDE OF THE FIRST HARMONIC OF THE SOLAR-DIURNAL VARIATION OF COSMIC RAYS DURING THE IGY PERIOD BASED ON THE DATA OF OBSERVATIONS WITH NEUTRON MONITORS AT SEA LEVEL AND AT HIGH ELEVATIONS

Stations	Geomagnetic latitude	t_1 max, hour	r_1 in %	Stations	Geomagnetic latitude	t_1 max, hour	r_1 in %
	Sea level						
Resolute	82.9°	17.6	0.14	Alma-Ata	33.0	14.0	0.25
Churchill	69.7	15.4	0.32	Machapu	21.3	10.7	0.24
Upsala	58.6	14.5	0.27	Ahmadabad	13.9	12.9	0.33
Deep River	57.5	14.8	0.37	Lae	—16.0	9.9	0.24
Ottawa	56.8	14.6	0.31	Wellington	—51.5	14.8	0.30
Leeds	56.3	13.3	0.28	Mawson	—73.1	17.8	0.22
Herstmonsex	53.5	14.4	0.25				
Chicago	52.6	14.7	0.31		High elevation		
Gottingen	52.3	14.2	0.31				
Yakutsk	51.0	14.5	0.21	Sulphur	58.2	14.9	0.32
Lincoln	50.8	15.4	0.33	Washington	55.6	13.5	0.34
Weisenau	49.0	14.0	0.32	Zugspitze	48.2	14.7	0.39
Berkeley	44.1	14.7	0.30	Climax	48.1	15.7	0.29
Rome	42.5	13.9	0.26	Norikura	25.6	13.3	0.33
				Guadacanal	0.6	13.0	0.28
				Huancayo	0.6	12.7	0.22

that, based on the data of the neutron and hard components, during the period of the solar activity maximum the energy spectrum of the solar-diurnal anistropy has a power-law form with an exponent between 0.35 and 0.5 [44, 49-51]. In [52, 53], based on data on the neutron component during this same period, an energy spectrum was obtained in which the exponent equalled zero. Let us attempt to explain the reason for the difference between the results when, based on the same data during the same period, incongruent results are obtained.

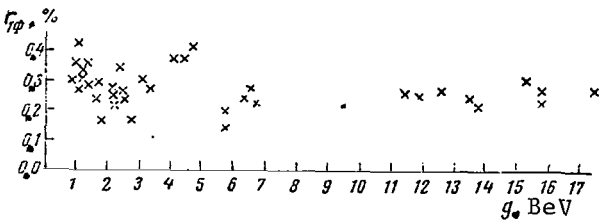


Figure 15. The amplitude of the first harmonic as a function of the cutoff energy g based on data in [52].

In Figure 15 the amplitude of the first harmonic, taken from [52], is presented as a function of the cutoff rigidity. The energy spectrum calculated on the basis of these data by means of the coupling coefficients taken from [2] has a power-law form with the exponent $\gamma = 0.25$.

In order to compare the results in [52] with the results in [53, 54], let us introduce a correction in [52] for the asymptotic angle of arrival of particles.

In Figure 16a the behavior of the diurnal variation amplitude is presented as a function of the asymptotic angle of arrival of particles (the Φ value is taken from [55][(1)]).

In Figure 16b and 16c the behavior of the diurnal anistropy amplitude is presented as a function of asymptotic latitude based on the data in [54] and [53] respectively.

Figure 16 shows that in the region of high latitudes the behavior of the amplitude as a function of Φ satisfies the function cos Φ (the

(1) Let us note that the Φ values based on data in [55] and [56] agree well.

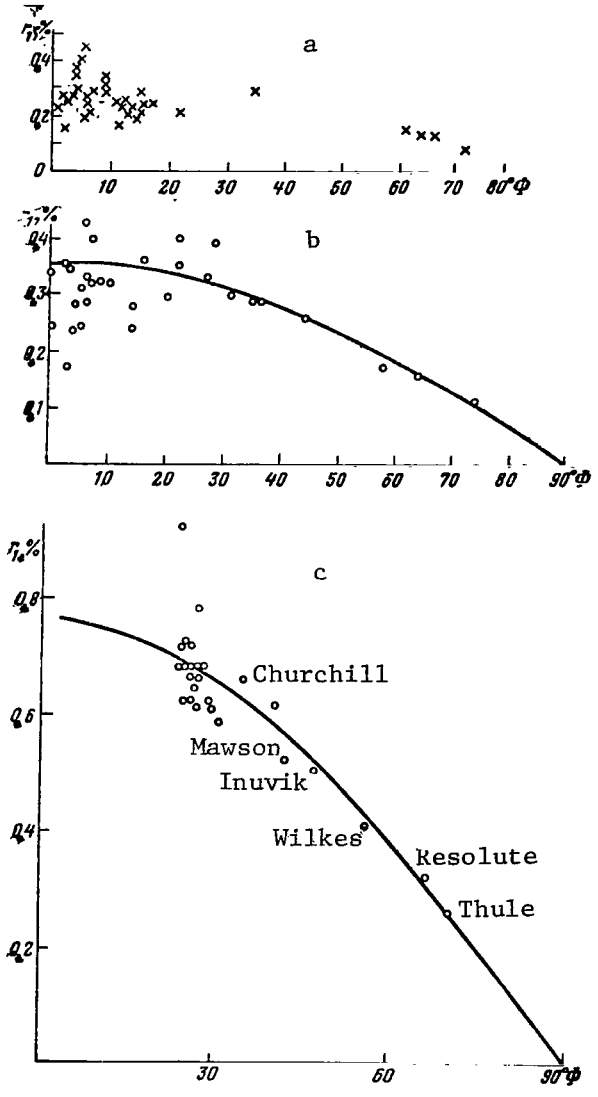


Figure 16. Amplitude of the first harmonic as a function of asymptotic latitude Φ

a - based on the data in [52];
b - based on the data in [54];
c - based on the data in [53].

curve in Figure 16c). The behavior of the diurnal variation amplitude (corrected for the asymptotic angle) as a function of the cutoff rigidity is shown in Figure 17 based on the data in [52]. In Figure 18a,b, it is shown based on data in [53] and [54] respectively. The energy spectrum calculated on the basis of these data has the power-law form: $\frac{\delta D}{D}(\varepsilon) = a\varepsilon^{-\gamma}$ with the exponent $\gamma \approx 0{,}2 \div 0{,}3$.

Thus, the observed difference in the form of the spectrum in [52] and [54] is caused by the calculation method.

Let us investigate what comprises the difference between the form of the energy spectrum calculated in [53] and [54].

As is seen from Figure 16c (where the values of the diurnal variation amplitude are presented as a function of asymptotic latitude), an agreement between the theoretical calculations and the experimental data is observed for latitudes above 30°. At latitudes lower than 30°, the experimental values lie below the theoretical values. Therefore, the corrected values for the stations having low latitudes do not lie on the theoretical line, in accordance with which the anisotropy has a constant value. The slope of the experimental points as a function of the energy gives a power-law spectrum with an exponent of 0.25. Considering the foregoing, one may conclude that the difference in the /30 spectrum form is caused basically by the calculation method and by the approximations which are assumed by the authors, in particular in [53]. Considering these factors, one can say that in [44, 49, 50, 52, 53] and based on the converted data in [52, 53, 57] the anisotropy energy spectrum during the second half of 1957 and all of 1958, based on the data of various authors, has a power-law form with an exponent of 0.25-0.5.

Let us investigate the change in the anisotropy energy spectrum with a decrease in solar activity. In [53, 54, 58-60] studies were conducted on the basis of data on the global network of stations recording the neutron component. Periods were selected when Forbush effects and magnetic storms were not observed at the earth's surface. All data were corrected for

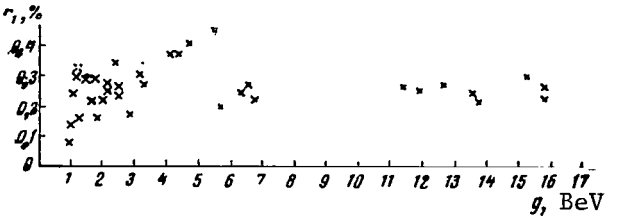


Figure 17. Amplitude of the first harmonic r_1 corrected for asymptotic latitude Φ as a function of the cutoff energy g, based on the data in [52].

the barometric effect. A harmonic analysis was conducted according to local time, based on data averaged over a month. Days were selected when they were all two-hour values. Before averaging, graphs were plotted from which the instrumental errors of various kinds were recognized and then eliminated. To increase the statistical precision, a second averaging was conducted along latitudinal zones with mean cutoff rigidities of 1, 1.5, 2.5, 3.9, 6.0 and 12.7 BeV. The cutoff rigidities for each station were taken from [61]. Figure 19 presents the data, averaged over years and zones, on the amplitude of the first harmonic during the period from 1958 through 1962. It is seen that at the high-latitude stations (rigidity threshold of 1.0 BeV) the amplitude from 1958 through 1962 increased from 0.2 to 0.3%. An increase in the amplitude in 1960 and 1962 of 0.05% is observed at stations located in the latitudinal-zone with a mean threshold rigidity of 1.4 BeV. At the mid-latitude and low-latitude stations, the amplitude of the diurnal variation decreased slightly.

In Table 10, the ratio of the mean annual values of the first harmonic amplitude for 1958 is presented in comparison with the corresponding amplitudes of 1959-1962 for the equatorial stations (ε = 12.8 BeV), for the mid-latitude stations (ε = 3.0 BeV), and for the high-latitude stations (ε = 1.2 BeV).

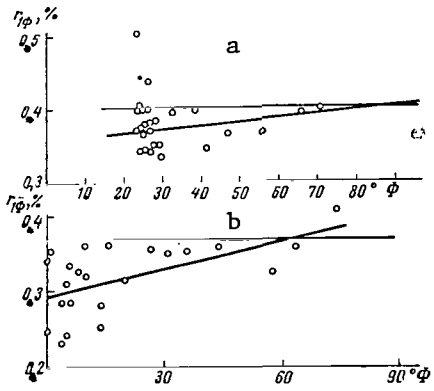


Figure 18. Behavior of $r_{1\Phi}$ as a function of Φ based on the data in [53] (a) and [54] (b).

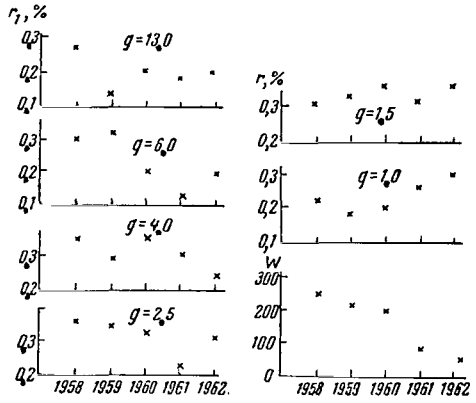


Figure 19. Change in the mean annual values of the amplitude of the diurnal variation r_1 in 1958-1962 for various cutoff energies g (in BeV). The change of the mean annual sunspot number W also is shown.

It is seen that the amplitude at the high-latitude stations in 1960-1962 slightly increased; the amplitude at the middle-latitude and equatorial stations during 1959-1962, on the other hand, was reduced.

With such a change of the first harmonic amplitudes, it would appear that the spectrum must be softened with a decrease in solar activity. When calculating the spectrum, it is necessary to take into account the change in the /31 coupling coefficients, which increase with a decrease in solar activity, especially in regions of small and medium energies. When this is done, one finds that the spectrum does not become softer, but remains constant or even hardens slightly. Second, it is not impossible that the source of the anistropy, with a decrease in solar activity, acts more effectively on the particles which arrive perpendicularly to the plane of the ecliptic, and its effectiveness is weakened with respect to particles reaching the earth in the plane of the ecliptic.

TABLE 10. RATIOS OF THE MEAN ANNUAL VALUES OF THE AMPLITUDE OF THE DIURNAL VARIATION OF COSMIC RAYS

Cutoff energy in BeV	1958/1959	1958/1960	1958/1961	1958/1962
1,2	1,06	0,96	0,94	0,95
3,0	1,10	1,05	1,32	1,34
12,8	1,54	1,22	1,45	1,12

Now let us find the spectrum of the short-period variations. On the basis of the mean monthly data for the first harmonic, taking into account the latitudinal variations, the energy spectrum was calculated for each month by means of the coupling coefficients [62].

The spectrum in the interval of energies 3-15 BeV is represented in the power-law form $\frac{\delta D}{D}(\varepsilon) = a\varepsilon^{-\gamma}$. The values of the exponent γ which were found are presented in Table 11 (columns 3, 7, 11, 15). It is seen that γ varies from 0.25 to 0.5. In columns 4, 8, 12 and 16 of the same table, the values of the exponent are presented; the calculation was conducted with consideration of the dependence of the source intensity on latitude [1, 2, 55, 63]. It is seen that the change in the spectrum exponent in time is the same, only the value is slightly higher. Here, the mean monthly values of the sunspot number also are presented (columns 2, 6, 10, 14). In the last row, the same values averaged over a year are presented.

It is seen that the energy spectrum of the diurnal variation is not softened when solar activity decreases, but remains practically unchanged or even becomes slightly harder. In every case in 1960 and 1962, the exponent was somewhat lower than in 1957 and 1958 (it is obvious that here one can talk only about the trend, since the error for the exponent was $\pm$ 0.04 and the data, with consideration of the error, practically overlap).

TABLE 11. CHANGE IN TIME OF SUNSPOT NUMBER W, INTENSITY OF THE SOURCE OF DIURNAL VARIATION (a) AND THE EXPONENT IN THE VARIATION SPECTRUM ON THE ASSUMPTION THAT SOURCE INTENSITY DOES NOT DEPEND ON LATITUDE (γ_1) AND CONSIDERING THE COSINE-TYPE DEPENDENCE OF LATITUDE (γ_2)

Years	1958				1959				1960				1961				1962			
Months	W	γ_1	γ_2	a	W	γ_1	γ_2	a	W	γ_1	γ_2	a	W	γ_1	γ_2	a	W	γ_1	γ_2	a
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
January	289	0,42	0,48	0,32	298	0,41	0,47	0,02	176	0,34	0,31	0,06	142	0,38	0,35	0,03	43	0,25	0,31	0,02
February	190	0,33	0,34	0,17	—	—	—	—	138	0,15	0,18	—0,13	63	0,38	0,37	0,18	67	0,36	0,35	0,22
March	—	—	—	—	240	0,44	0,30	0,28	151	0,28	0,30	0,05	65	0,32	0,39	—0,16	50	0,29	0,33	0,19
April	209	0,39	0,39	0,39	218	0,40	0,40	0,27	169	0,30	0,30	0,30	95	0,33	0,37	—0,12	58	0,28	0,29	0,08
May	223	0,35	0,35	0,35	177	0,46	0,50	0,33	166	0,27	0,28	0,02	66	0,40	0,40	0,27	52	0,38	0,38	0,25
June	257	0,33	0,30	0,33	255	0,46	0,45	0,37	164	0,36	0,38	0,07	115	0,38	0,41	0,22	55	0,33	0,32	0,13
July	258	0,42	0,40	0,42	240	0,40	0,44	0,21	171	0,33	0,38	0,11	76	0,39	0,39	0,06	28	0,36	0,40	0,09
August	315	0,36	0,39	0,36	214	0,32	0,33	0,004	57	0,26	0,35	0,03	89	0,34	0,35	0,31	26	0,32	0,34	0,14
September	365	0,42	0,40	0,42	—	0,38	0,42	0,05	166	0,30	0,31	0,03	70	0,26	0,31	0,11	56	0,21	0,31	0,24
October	184	0,46	0,45	0,46	151	0,47	0,57	0,37	101	0,32	0,33	0,13	52	0,30	0,34	—0,01	—	—	—	—
November	180	0,37	0,35	0,37	168	0,34	0,36	0,13	—	—	—	—	39	0,35	0,35	—0,22	—	—	—	—
December	270	0,42	0,37	0,42	—	—	—	—	149	0,30	0,35	—0,06	36	0,39	0,40	0,01	—	—	—	—
Mean-annual	249	0,38 0,39	0,38	0,14	218	0,41	0,41	0,18	193	0,30	0,40	0,06	78	0,36	0,38	0,08	48	0,30	0,38	0,09

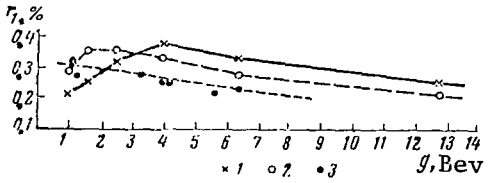


Figure 20. Amplitude of the first harmonic as a function of the cutoff energy g for various periods.

1 - 1958; 2 - 1962; 3 - 1964.

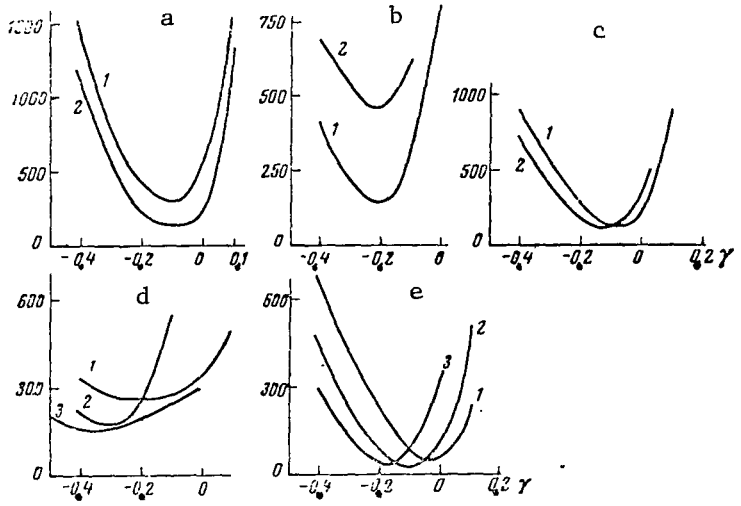


Figure 21. Change in the exponent γ of the energy spectrum of the diurnal variation in time (the root-mean-square deviations of the amplitude are plotted along the ordinate axis in relative units) based on the data in [64] and [65].

a - 1958; 1 - a_n = 0.35, 2 - a_n = 0.41;

b - 1959: 1 - a_n = 0.43, 2 - a_n = 0.38;

c - 1960: 1 - a_n = 0.37, 2 - a_n = 0.40;

d - 1961: 1 - a_n = 0.24, 2 - a_n = 0.35, 3 - a_n = 0.30;

e - 1964: 1 - a_n = 0.27, 2 - a_n = 0.30, 3 - a_n = 0.33.

Let us discuss the results of investigating the solar-diurnal variations of the neutron component of cosmic rays during January-December 1964 based on the data of the global network of stations located at various latitudes [64]. The data corrected for pressure were selected only during magnetically quiet periods. The same as in the previous years, the harmonic analysis was conducted on the basis of the mean monthly values, and the first and second harmonics of the diurnal variations were determined.

In Figure 20 the amplitude of the first harmonic is presented as a function of the magnetic cutoff rigidity. For the purpose of comparison, the values during 1958 (small crosses) and 1962 (small circles) are shown in the same figure. Figure 20 shows that the amplitude of the diurnal variation falls off at the middle and lower latitudes with a decrease in solar activity. At high latitudes, the solar-diurnal variation increases slightly with a decrease in solar activity, and at the minimum of solar activity it remains constant.

The energy spectrum of the solar-diurnal anistropy, calculated from data for 1964, has a power-law form with the exponent $\gamma = 0.35 \pm 0.04$ - - that is, it remains practically constant with a change in solar activity. The lower boundary of the spectrum is shifted from 6 BeV in 1957-1958 to 1.5-2 BeV in 1964. Judging from the amplitude change at the middle and lower latitudes, one can say that the intensity of the source responsible for the solar-diurnal anisotropy decreased from 1958 through 1964 by a factor of 1.5-1.7. /34

In [54, 58, 60] the change in the anistropy energy spectrum was investigated as a function of the decrease in solar activity. Using the experimental data in [54, 65], the exponent of the energy spectrum was calculated as a function of the various parameters of the diurnal anisotropy. The results of these calculations are presented in Figure 21. Figure 21 shows that the energy spectrum exponent lies between 0.1-0.25 with various values of a_n.

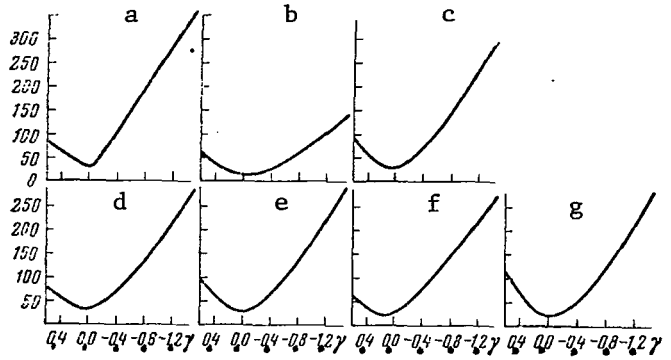


Figure 22. Change in the exponent γ of the energy spectrum of the diurnal variation in time (the root-mean-square deviations of the amplitude are plotted along the ordinate axis in relative units) based on the data in [53].

a - 1957-1958 (based on the data of 18 stations $\gamma_{ef} = 0.0$);

b - 1959 (based on the data of 8 stations $\gamma_{ef} = 0.0$);

c - 1960 (based on the data of 15 stations $\gamma_{ef} = 0.0$);

d - 1961 (based on the data of 16 stations $\gamma_{ef} = 0.0$);

e - 1962 (based on the data of 13 stations $\gamma_{ef} = 0.0$);

f - 1963 (based on the data of 14 stations $\gamma_{ef} = 0.2$);

g - 1964 (based on the data of 12 stations $\gamma_{ef} = 0.0$).

In [53] it is shown that the mean solar-diurnal variations satisfy the expression

$$\frac{\delta J(E)}{J(E)} = \begin{cases} C \cdot 40 \cdot 10^{-2} \cos(\theta - 35^\circ) \sin \xi & \text{with } E \leqslant 200 \text{ BeV} \\ 0 & \text{with } E \geqslant 200 \text{ BeV} \end{cases}$$

where (θ, ξ) are the spherical polar angles, whose origin coincides with the geographic north pole; θ is measured in the meridian plane which includes the sun. We referred above to the fact that the authors of [53] came to the conclusion that the energy spectrum of the solar-diurnal anistropy has a constant magnitude. In Figure 22 the change in the energy spectrum (of the effective

exponent γ) in time [53] is shown. Figure 22 shows that the anisotropy energy spectrum remains constant with a change in solar activity, and the upper boundary of the spectrum has the value E $\sim$ 200 BeV. The exponent during the entire period, except for 1963, equals zero. In 1963 the energy spectrum exponent had a positive value equal to 0.2 — that is, the energy spectrum in this period became slightly harder. The tendency of the anisotropy energy to harden with a decrease in solar activity was noted in [54, 60]. These results agree well with the data obtained earlier by us [51, 65] — the only difference is that in [51, 65] the exponent on the average equalled $\sim$ 0.4 and had a negative sign.

The authors of [48a], to explain the latitudinal effect of the diurnal variation, proposed a model in which there were two anisotropy sources: one (Δj_1) with a direction of 2000 hours was a remote source; the other (Δj_2) with a direction of 0800 hours was a close source

$$\Delta j_1(E, \psi) = K_1 E^{-(\gamma+m_1)} \cos\psi,$$
$$\Delta j_2(E, \psi) = K_2 E^{-(\gamma+m_2)} \cos(\psi - \Phi).$$

Here $E^{-\gamma}$ is the energy spectrum of the primary flux of the cosmic ray intensity; Φ is the angle between Δj_1 and Δj_2; ψ is measured counterclockwise. With the 2000-hour direction $\psi = 0$.

It is interesting to note that the directions Δj_1 and Δj_2 closely coincide /35 with the direction of the lines of force of the interplanetary magnetic field in the earth's vicinity. One can explain the diurnal anisotropy by the gradient of the cosmic rays in this case.

In [66] the authors attempted an analysis of the diurnal anisotropy for each day during the period from 1957 through April 1963 in the following way.

Method I. The first harmonics for each day were calculated in the following way:

$$\Delta J_i = J_i - \frac{1}{13} \sum_{j=i-6}^{i+6} J_j,$$

where J_i is the two-hour intensity value. Let us designate by A_Z and T_Z the amplitude and time of the maximum (UT) which were obtained from the data of the neutron monitor at Zugspitze, and by A_N and T_N the corresponding data for Norikura.

Method II. The differences in the variations are found

$$\Delta J_H = J(Z) - \frac{1}{3} J(Z) + J(S) + \frac{A_Z}{A_N} J(N) A(N) \text{ and } T_H \text{ from } \Delta J_H,$$

$$\Delta J_L = J(N) - \frac{1}{2} [J(N) + J(M)] A_L \text{ and } T_L \text{ from } \Delta J_L.$$

Here J(S) is the intensity at the station Sulphur; J(M) is the intensity at the station Mina-Aguilar.

Let us note that the calculations based on Method I are suitable only for quiet periods, but Method II distorts the results because of ΔJ.

An analysis showed that the calculations based on Method I give

$$A_Z, A_N \geqslant 0{,}1\% \text{ and } |A_Z - A_H| \leqslant 0{,}2,$$

and the calculation based on Method II gives

$$A_Z, A_N, A_H, A_L \geqslant 0{,}1\% \text{ and } |A_Z - A_H| \leqslant 0{,}2\%.$$

In Figure 23 the phase differences and amplitude ratios are presented for the stations Zugspitze and Norikura.

From Figure 23a it follows that

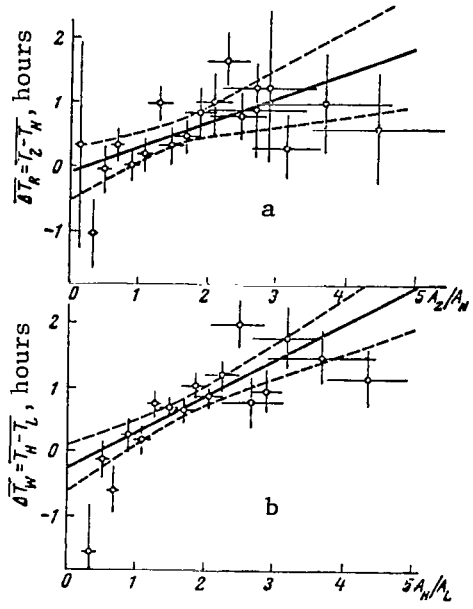


Figure 23. Data on the phase differences and amplitude ratios for the stations Zugspitze and Norikura calculated on the basis of Methods I and II (a,b).

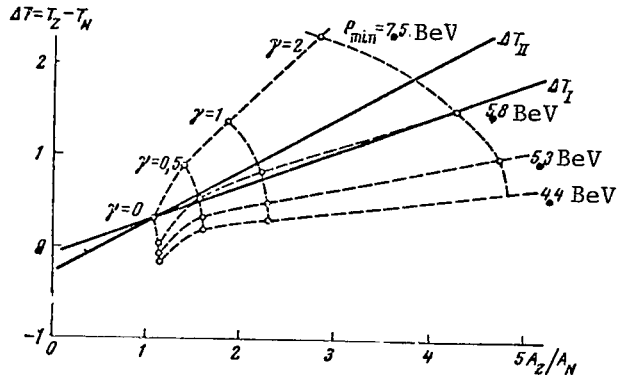


Figure 24. Comparison of the theoretical results of ΔT and A_Z/A_N (calculated with various values of P_{min} and γ) with the experimental data.

$$\overline{\Delta T}_R = -(0.07 \pm 0.04) + (0.38 \pm 0.12)\frac{A_Z}{A_N}.$$

and from Figure 23b:

$$\overline{\Delta T}_W = -(0.23 \pm 0.03) + (0.55 \pm 0.09)\frac{A_H}{A_L}.$$

The theoretical expected behaviors of ΔT as a function of A_Z/A_N for an energy spectrum in the form

$$\frac{\delta D}{D} = \begin{cases} Kp^{-\gamma} & \text{with } P \geqslant P_{\min}, \\ 0 & \text{with } P \leqslant P_{\min} \end{cases}$$

are presented in Figure 24 for the various values of γ and P_{min}. In this same figure, the experimental data for the stations Zugspitze and Norikura are presented. The calculations in [66] were conducted in accordance with [67-69].

The results of the analysis showed that the diurnal variations have amplitude ratios and a spectrum which, in the limits of errors, do not vary. The detailed analysis presented showed that no difference is observed in the spectrum as was indicated by the authors of [70] and that the diurnal variations have two types of spectra: one has a low threshold P_{min} and a positive exponent γ (this is observed only for semidiurnal variations, see [51, 54]), and the other has a high value of P_{min} and a negative exponent γ. The authors of [66] indicated that P_{min} constantly has the value $\sim$ 6 BeV.

Let us investigate how the strength of the source changes based on the /36
data in [53]. One can determine the strength of the source from the anisotropy amplitude change from the maximum to the minimum of solar activity. In Figure 25 the amplitudes of the diurnal variation are presented for the period from 1953 through 1965 [53]. The data were averaged over all the stations of the global network recording the neutron component of cosmic rays. Since in 1952-1955 there were only a few instruments, values should not be given for the points in 1953-1955. Therefore, let us compare the results of 1956-1958 — a maximum of solar activity — with the data of 1963-1965 — a minimum of solar activity (during 1965 the data were recorded only for the first half of the year). The data presented show that the source strength at the minimum of solar activity is smaller by a factor of 1.2 than at the maximum. In this case, the result is slightly lower, since at the various latitudes the amplitude of the solar-diurnal variations changed in opposite directions, and here the averaged data are cited for the various stations. It is necessary to point out the slightly increased amplitude of the diurnal variation in 1960 and 1962.

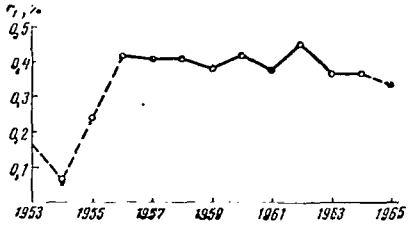


Figure 25. Change in the amplitude of solar-diurnal variations. in the period 1953-1965 based on averaged data of the global network of stations.

Let us investigate the data of the solar-diurnal variations during the period 1958-1961 which were obtained at various levels below the earth. Based on these data, in [47], a softening of the anisotropy energy spectrum was indicated with a decrease in solar activity — more precisely, the energy spectrum of the solar-diurnal anisotropy during the period 1958-1959 was described by the expression $\frac{\delta D(\varepsilon)}{D(\varepsilon)} \sim \varepsilon^{-0,5}$. The spectrum during the period 1960-1961 had the form

$$\frac{\delta D(\varepsilon)}{D(\varepsilon)} \sim \varepsilon^{-1}.$$

The experimental results during the period 1958-1959 [22, 71] are presented in Table 12, where A_h is the amplitude of the diurnal variation based on data corrected for the barometric pressure; t_h is the corresponding time of the maximum; A_{hW} is the amplitude of the diurnal variation based on data corrected for the barometric pressure and temperature; t_{hW} is the corresponding time of the maximum. For comparison, let us present the data for the solar-diurnal variations during the period 1958-1961 in accordance with [47] (Table 13). /37

From the data presented, with consideration of the remarks discussed above, the following conclusion can be drawn. The data for the cited interval of time in the limits of errors (that is, which we were able to verify — in the vertical direction) did not differ from one another. Therefore, it is impossible to make a judgement about the change in the energy spectrum, and also about any change in the amplitude in general. Regarding the level 60 m w.e., at this level, the errors are too large to definitely talk about the existence of solar-diurnal anisotropy.

TABLE 12. AMPLITUDE AND PHASE OF THE FIRST HARMONIC OF THE DIURNAL VARIATION OF THE HARD COMPONENT OF COSMIC RAYS BASED OBSERVATIONAL DATA FOR YAKUTSK IN 1958-1959 OBTAINED WITH CROSSED TELESCOPES

Level of observation in m,w.e.	Vertical				South				North			
	Considering the correction for the barometric effect		Considering the correction for the barometric and temperature effects		Considering the correction for the barometric effect		Considering the correction for the barometric and temperature effects		Considering the correction for the barometric effect		Considering the correction for the barometric and temperature effects	
	A_h, %	t_h	A_{hW}, %	t_{hW}	A_h, %	t_h	A_{hW}, %	t_{hW}	A_h, %	t_h	A_{hW}, %	t_{hW}
0	0,18	15,5	0,34	14,8	0,21	16,7	0,37	16,0	0,14	14,1	0,30	14,1
7	0,16	15,7	0,24	15,4	0,19	16,7	0,27	16,4	0,12	14,2	0,20	14,2
20	0,12	15,8	0,14	15,8	0,16	17,3	0,18	17,0	0,10	14,7	0,12	14,6
60	0,04	17,8	0,04	17,0	0,09	17,0	0,08	17,0	0,02	14,6	0,02	14,7

TABLE 13. THE FIRST HARMONIC OF THE DIURNAL VARIATION WITH A CORRECTION FOR METEOROLOGICAL EFFECTS

Level of observation in m.w.e.	Direction	1958—1959		1960—1961	
		r_1, %	$t_{1\,max}$, hrs	r_1, %	$t_{1\,max}$, hrs
0	Vertical	0.25±0.03	15.2±0.5	0.17±0.03	15.7±0.7
	South	0.26±0.03	16.0±0.4	0.19±0.03	17.0±0.7
	North	0.21±0.03	14.1±0.6	0.18±0.03	14.6±0.7
7	Vertical	0.17±0.01	15.7±0.4	0.10±0.01	16.8±0.4
	South	0.20±0.01	16.7±0.3	0.11±0.01	17.8±0.4
	North	0.12±0.01	14.2±0.7	0.10±0.01	14.8±0.4
20	Vertical	0.12±0.01	15.8±0.7	0.06±0.01	17.0±0.7
	South	0.16±0.01	17.0±0.4	0.08±0.01	18.0±0.5
	North	0.10±0.01	14.7±0.7	0.06±0.01	15.2±0.7
60	Vertical	0.5±0.02	16.5±1.6	0.03±0.02	19.0±3.0
	South	0.11±0.03	16.6±1.2	0.04±0.03	14.0±3.0
	North	0.04±0.02	14.6±3.0	0.02±0.03	6.0±6.0

6. Change in the Amplitude and Phase of Anisotropy Based on the Data for Different Directions

Let us investigate the data concerning the solar-diurnal variation which were presented in [72] where the anisotropy of the cosmic rays in the hard component was studied. An analysis was made of which were obtained by means of an azimuthal telescope with directions to the west and to the east during the period 1958 and 1964. The instrument was installed in Bolivia at an altitude of 5,200 m above sea level (the geomagnetic coordinates are -4.8°, +0.8°). Moreover, the results of the first harmonic based on the data of neutron monitors at Huancayo and Norikura are presented for this same period.

In Table 14 the values of the amplitude R_1 of the first harmonic of the diurnal variation are presented and also the time of the maximum T_1. The results of the calculations are given both for the data corrected for temperature and also for the uncorrected data. The table shows that the amplitude of the diurnal variation of cosmic ray intensity (direction to the east) at the solar activity maximum is two times larger than at the minimum based on the data corrected and uncorrected for the temperature effect. The data for the western direction give a similar amplitude at the maximum and minimum of solar activity (when a correction is not introduced for temperature). After correction of the data for temperature, the amplitude of the diurnal variation (western direction) at the minimum of solar activity is four times smaller than at the maximum.

The phase of the diurnal variation based on crossed telescopes data was shifted by 1.5 - 2 hours to a later time from the maximum to the minimum of solar activity.

Thus, the data from the crossed telescopes of the station at Chakaltaya do not contradict the results obtained by us based on the data of the neutron component of cosmic ray intensity [54, 65].

TABLE 14. VALUES OF THE AMPLITUDE OF THE FIRST HARMONIC (R_1) OF DIURNAL VARIATION AND THE TIME OF THE MAXIMUM T_1

Year	Mean annual sunspot number	Uncorrected for temperature effect				Corrected for temperature effect			
		East		West		East		West	
		R_1 in %	T_1 in hr	R_1 in %	T_1 in hr	R_1 in %	T_1 in hr	R_1 in %	T_1 in hr
1958	184.6	0.06± 0.02	1.07± 0.62	0.07± 0.02	4.92± 0.53	0.07± 0.02	4.92± 0.53	0.07± 0.02	4.92± 0.53
1964	10.2	0.06± 0.01	2.92± 0.32	0.09± 0.01	3.77± 0.22	0.06± 0.01	2.92± 0.32	0.09± 0.01	3.77± 0.22

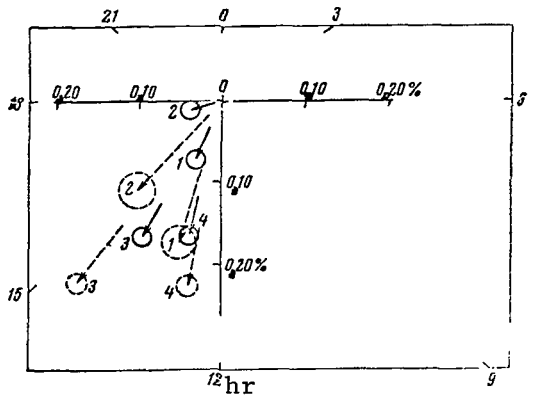


Figure 26. Data on the first harmonic at Chakaltaya based on data on hard component observations: from the east (1), from the west (2) and based on the data on neutron component observations at the stations Norikura (3) and Huancayo (4) in 1958 (dashed line) and in 1964 (solid line).

Figure 26 shows a harmonic diagram giving data for the period of the maximum (1958) and minimum (1964). Besides the data of the crossed telescopes from the station at Chakaltaya, the data of the neutron monitors from the stations at Norikura and Huancayo are also presented in the same figure. Figure 26 shows that, based on the neutron component data, the amplitude of the diurnal variation at the low-latitude stations is decreased by a factor of 1.3. The reason for the sharp decrease in the diurnal variation amplitude from the maximum to the minimum of solar activity based on the data of the crossed telescopes may be that the method of introducing the temperature correction is not precise. Let us point out that, based on neutron component data, the time of maximum of the diurnal anisotropy from the maximum to the minimum of solar activity at Huancayo station, in the limits of error, remains constant, but at Norikura station /38 it was shifted by approximately 0.5 hours to a later time. Let us compare the data of the crossed telescopes obtained at Yakutsk with the data listed above (unfortunately, here we have directions only to the south and north). Table 13 shows that the diurnal variation amplitude at the earth's surface, within the limits of error, during the period 1958-1961, remains constant. At a depth of 7 m w.e. the anisotropy in the southern direction is reduced by a factor of two; for the northern direction it remains constant. At a depth of 20 m w.e. the amplitude from the southern direction decreased by a factor of two, and from the north it decreased by a factor of 1.5. At a depth of 60 m w.e., within the limits of error, no change of any kind was observed.

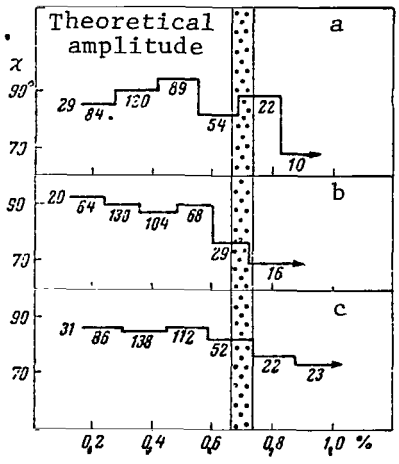


Figure 27. Change in the diurnal anisotropy source phase as a function of its amplitude at the stations:

a - Churchill; b - Deep River; c - Dallas; the numbers are the number of days with given anisotropy amplitude and phase.

The phase of the solar-diurnal variation, within the limits of error, based on the data in [47] remains constant, which contradicts the data in [72]. It is necessary to mention once again that in these works data for different ent directions were presented.

Let us also investigate in this section the change in solar-diurnal variation amplitude as a function of the phase during the corresponding period. The authors of [53] succeeded in solving this problem after recording the neutron component of the cosmic ray intensity by means of superneutron monitors, and they were able to study the diurnal variations for each day with a high precision. Figure 27 shows that for Dallas and Deep River with an increase in the amplitude (starting from 0.6%), source phase is shifted to earlier hours. For the high-latitude station Churchill up to an amplitude of 0.8% there is no such dependence. In fact, there is a reverse tendency — that is, with an increase in the diurnal variation amplitude, up to 0.6% the phase is shifted to a later time. /39

7. Direction Toward the Anisotropy Source and its Change in Time

Having determined the energy spectrum of the diurnal variations in various periods of solar activity, we were able to calculate the direction of the anisotropy source in accordance with method [1]. Let ψ (ε) be the angle between the projection of the direction of motion of a particle at

TABLE 15. BEHAVIOR OF χ AS A FUNCTION OF g IN 1958-1962

g, BeV	χ					g, BeV	χ				
	1958	1959	1960	1961	1962		1958	1959	1960	1961	1962
1,00	81,2	90,5	92,0	92,0	92,0	4,00	59,3	52,0	85,0	74,5	56,5
1,50	84,3	103,5	111,0	99,0	96,0	6,00	62,7	87,0	85,5	94,5	82,5
2,15	67,9	84,0	79,5	75,0	67,5	12,00	62,6	125,0	89,0	87,5	73,8

infinity onto the plane of the geomagnetic equator and the projection onto that same plane of the radius of the vector drawn from the center of the Earth to the point on earth's surface where the particle must fall. values of $\psi_\lambda(\varepsilon)$ were taken from [55]. Knowing the time of the maximum of the diurnal variation and the calculated value of ψ, we determined the direction to the anisotropy source in the plane of the geomagnetic equator in an eastern direction with respect to the earth - sun line:

$$\chi = \psi + 15\,(t_{\max} - 12).$$

In Table 15, the values of χ are presented for the various periods being studied for the detectors located at high, middle and low latitudes. /40

The error for χ was $\pm$ 0.8°. It was determined by the error in the time of the maximum ($\pm$ 0.05 hours for the mean annual values). In the high-latitude region χ is larger than in the middle and low-latitude regions. This agrees with the data concerning the distribution of the anisotropy source in the plane perpendicular to the plane of the ecliptic. It is necessary to mention that in the period 1960-1962, χ is slightly larger than in 1958 at high and low latitudes, which also is clearly seen from Table 15.

In Figure 28 the values of the direction toward the source (the angle χ measured to the west from the direction to the sun) are presented. Starting from 1957, calculations of the anisotropy energy spectrum and the time of the

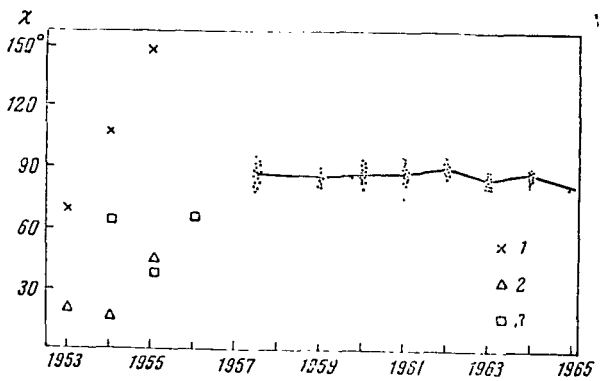


Figure 28. The position of the anisotropy source (the angle to the west of the earth - sun line) before 1957 - based on the data of observations at the stations: 1 - Climax; 2 - Huancayo; 3 - Ottawa; after 1957 - based on observation data for the global network of stations.

maximum were made based on the data of the global network of stations recording the neutron component of the intensity of cosmic rays. The energy spectrum of the diurnal anisotropy in this work [53, 57] was constant, and did not change with the cycle of solar activity. The angles $\psi_\lambda(\varepsilon)$ were taken from [55].

The data cited indicated that from 1957 through 1965, the direction to the source, based on the data of various stations, was found in the region 80-100° and did not change with solar activity, at least in the last eight years. As regards the preceding years, where only the data from three stations are presented, it is very difficult to make a judgment concerning any kind of law governing the behavior.

In Figure 29 the values of the direction toward the source of the diurnal variation source are presented for the period from 1932 through 1955 and a clear 22-year variation is seen. These results were calculated from data on the hard component which, to a strong degree, is subjected to the temperature effect. The precision in introducing the correction to these data up to the present time is not well-defined [1, 12, 13].

8. Seasonal Changes in the Solar-Diurnal Variation of Cosmic Rays

Calculations which were made in 1957 by one of the authors [1] showed that the misalignment of the axis of the earth's rotation with the perpendicular to the plane of the ecliptic, when the intensity of the anisotropy source depends on the asymptotic latitude of the arrival of particles, must lead to a seasonal change in the solar-diurnal variation of cosmic rays.

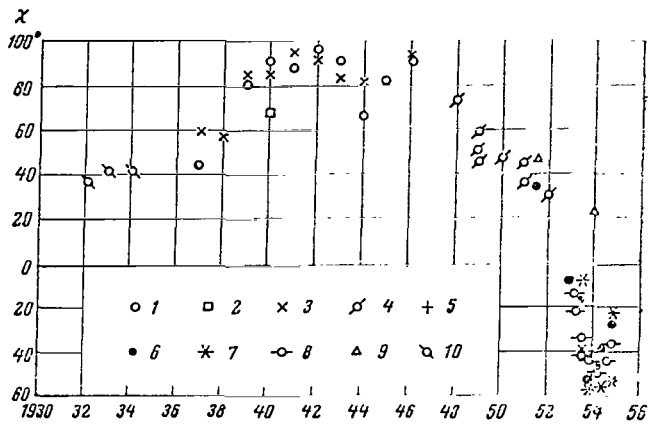


Figure 29. Change with time of the direction to the anistropy source based on observational data at the stations: 1 - Cheltenham; 2 - Berlin; 3 - Christchurch; 4 - Manchester; 5 - Stockholm; 6 - Moscow; 7 - Irkutsk; 8 - Tbilisi; also data with corrections for the temperature effect; 9 - Moscow; 10 - Hafelenar.

Unfortunately, up to the present there is no experimental verification of these calculations. To achieve such a verification by means of data from recording the hard component of cosmic rays is impossible, because of a temperature effect which is difficult to eliminate and also because of large seasonal changes. At present, this may be done from observations of the neutron component. It is important to emphasize that the discussed seasonal change in the observed diurnal variation must occur independently of the nature of the mechanism responsible for the anisotropy of cosmic rays in interplanetary space. This is seen from Figure 30, where the change in the asymptotic latitude Φ of particle arrival with the transition from summer (Φ_s) to winter (Φ_w) is shown, for an anisotropy source with the direction from the sun (a), and the latitude change with the transition from the spring (Φ_{sp}) to fall (Φ_f) for the anisotropy source with a direction of 90° to the west from the sun (b). If the source intensity decreases with an increase in symptotic latitude, then for an anisotropy source with the direction from the sun one should expect a maximum of the diurnal variation amplitude in the summer, and a minimum in the winter. For an anisotropy source with a direction 90° to the west of the sun, a maximum of the amplitude must be observed in the spring, and a minimum in the fall. If, for example, the source intensity decreases with an increase of Φ as cos Φ, then the expected amplitude of the seasonal wave with respect to the change in the diurnal variation amplitude at a point which is characterized by the mean asymptotic latitude $\delta < |\Phi_1| < \frac{\pi}{2} - \delta$ will be

/41

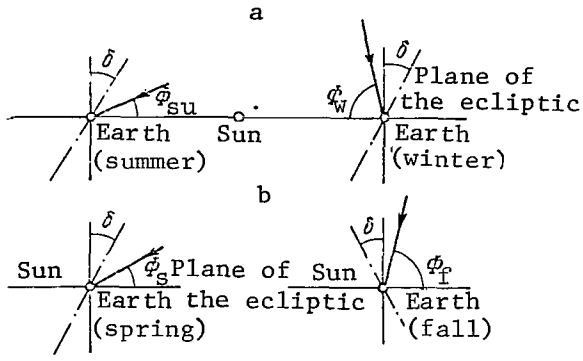


Figure 30. Change in asymptotic latitude Φ of particle arrival with transition from summer (Φ_{su}) to winter (Φ_w) for an anisotropy source with direction from the sun (a) and the change in latitude with transition from spring (Φ_s) to fall (Φ_f) for an anisotropy source with a direction 90° to the west of the sun. The angle δ = = 23.5° is the angle of inclination of the axis of rotation of the earth to the perpendicular to the ecliptic plane.

$$\alpha \approx \frac{\cos(|\Phi_1| - \delta) - \cos(|\Phi_1| + \delta)}{2\cos\Phi_1} = \sin\delta \cdot \operatorname{tg}|\Phi_1|,$$

that is, it may reach values of 50%. Here Φ_1 is the asymptotic latitude for a given point of observation and a particular secondary component with respect to the earth's geographic equator; δ = 23.5° is the angle between the axis of the earth's rotation and the perpendicular to the plane of the ecliptic. If $|\Phi_1| < \delta$ or $\frac{\pi}{2} - \delta < |\Phi_1| < \frac{\pi}{2}$, the picture of the diurnal variation amplitude change is slightly more complicated (thus, for example, with $|\Phi_1| < \delta$ two maxima with unequal amplitudes will be observed in a year; the amplitudes of these two maxima will be the same only when $|\Phi_1| = 0$ see [1], §27.4). The picture is considerably more complicated with the presence of two anisotropy sources with a direction of 0 and 90° to the sun (especially if the intensity and angular distribution change during the year because of a change in solar activity). In a rigorous analysis, it is necessary to keep in mind also the inclination of the plane of the ecliptic to the plane of the helioequator, which also must lead to an additional modulation of the solar-diurnal variation of cosmic rays [73].

From what was said above, it follows that the amplitude of the seasonal change in the solar-diurnal variation of cosmic rays may reach 50% of the mean annual value of the amplitude of the diurnal (or semidiurnal) wave, and /42 the character of this change must be rather complex. It is very important to obtain information concerning the seasonal changes in the solar-diurnal

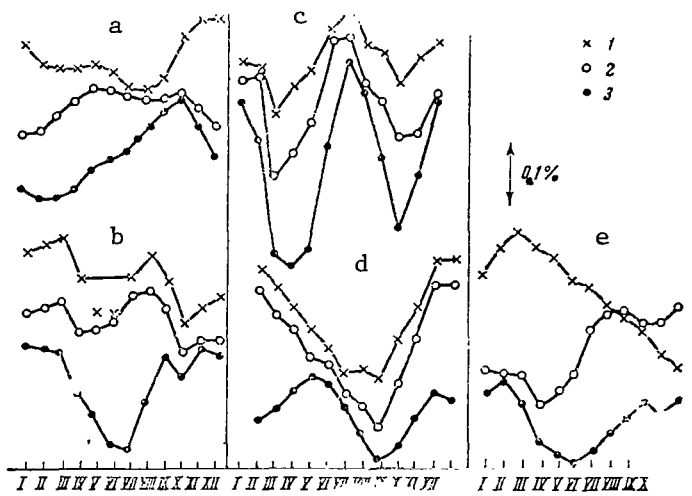


Figure 31. Seasonal anisotropy changes in 1958-1962 (a - e) 1 - Based on observational data at high latitudes; 2 - The same in the middle; 3 - The same at low latitudes.

variation of cosmic rays, since this gives additional information about the mechanism leading to formation of cosmic ray anisotropy in interplanetary space.

In this paper an analysis is made of the solar-diurnal variation in the intensity of the neutron component of cosmic rays, based on data from the network of stations during the period 1958-1962. For the purpose of finding these variations, the mean monthly two-hour intensities of neutrons for the indicated period were used. To increase the precision of the results, a second averaging of the data was carried out along the zones of stations [74].

All the stations (25-30 in various periods) were divided into three zones with mean cutoff energies of 1.5, 4.2 and 12.0 BeV. Then for each year the average amplitude of the solar-diurnal variation was found along the zones. The deviations of the amplitude values from the mean values indicated the change in the solar-diurnal variation during a year. In Figure 31 the changes of the solar-diurnal variation are presented from 1958 through 1962. The upper curves are the data from the high latitude zone; the middle curves are the data from the middle latitude zone, and the lower curves are from the equatorial stations. Figure 31 shows that in 1958 an annual change in the amplitude of the solar-diurnal variation took place with a single maximum in all zones. In 1959, a single, clearly-expressed maximum was observed at the equatorial stations, and in the middle and high-latitude zones two maxima were observed.

An especially large seasonal change in the solar-diurnal variation amplitude with two maxima occurred in 1960.

In 1961, a seasonal change in the diurnal variation with two maxima also occurred at the equatorial stations, and a seasonal change with one maximum took place in the middle latitude and high latitude zones. In 1962 a seasonal change in the diurnal variation with a single maximum was observed in all latitudinal zones. Let us note that only in 1960 was the amplitude change in all latitudinal zones the same with respect to phase, whereas in the remaining years a dissimilar change was observed in the various latitudinal zones — that is, in the various regions of primary particle energies.

To make a detailed investigation of the seasonal change in the solar-diurnal variation, we performed a harmonic analysis based on the deviations of the amplitude of the first harmonic from the mean annual values. The /43
results of calculating the annual and semi annual waves of the seasonal change of the diurnal variation amplitude are presented in Table 16.

From Table 16 shows that the amplitude of the first harmonic of the seasonal change in the diurnal variation was approximately the same at the high-latitude and low latitude stations in 1958-1960. In 1961 it increased by more than a factor of two, and then it slightly decreased in 1962. At the equatorial stations, the opposite picture was observed. The analysis which was made showed that very substantial seasonal changes in the diurnal variation of cosmic rays are actually observed. The amplitude changes are close to those expected because of the misalignment of the earth's axis of rotation with the perpendicular to the plane of the ecliptic when the source intensity depends on the asymptotic latitude of particle arrival. From the results presented, it also follows that two anisotropy sources of the cosmic rays are almost always simultaneously present — a radial and a tangential one, whose intensity and relative role in turn noticeably varied during the period of time being studied (from 1958 through 1962).

TABLE 16. SEASONAL CHANGES OF THE FIRST AND SECOND HARMONICS OF THE DIURNAL VARIATION

Years	Mean cutoff energy in Bev	Mean-annual value of the amplitude of the diurnal variation in %	First and Second Harmonics of the Seasonal Change of the Diurnal Variation			
			r_1 in % of A_1	r_2 in % of A_1	t_1 in days & months	t_2 in days & months
1958	1.5	0.281	13.9	19.4	Sept 27	May 13 & Nov 13
	4.2	0.384	6.9	7.8	May 5	Apr 1 & Oct 1
	12.0	0.353	18.2	9.7	July 5	Mar 21 & Sep 21
1959	1.5	0.300	11.6	25.1	Dec 3	Apr 22 & Oct 22
	4.2	0.323	2.9	18.7	Jan 15	Apr 6 & Oct 6
	12.0	0.251	29.7	12.7	Oct 12	Jun 11 & Dec 11
1960	1.5	0.349	8.5	14.5	Jun 3	Feb 8 & Aug 8
	4.2	0.393	11.9	22.6	May 15	Feb 21 & Aug 21
	12.0	0.298	17.5	51.0	July 17	Mar 3 & Sep 3
1961	1.5	0.334	24.8	9.4	Oct 14	May 7 & Nov 7
	4.2	0.300	30.1	17.4	Oct 25	May 15 & Nov 15
	12.0	0.197	17.4	32.1	Dec 25	Apr 19 & Oct 19
1962	1.5	0.402	15.9	7.2	Jan 20	May 21 & Nov 21
	4.2	0.368	13.6	11.6	Jun 26	May 9 & Nov 9
	12.0	0.234	21.0	17.0	Oct 12	May 19 & Nov 19

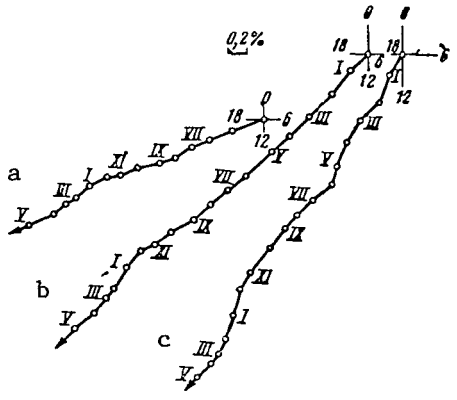


Figure 32. Mean monthly values of diurnal anisotropy vectors in the period 1964-1965 at the stations: a - Churchill; b - Deep River; c - Dallas.

9. Diurnal Anisotropy of Cosmic Rays in a Solar Activity Minimum

The data from the neutron supermonitors permitted us to carry out a detailed study of the diurnal variations, not averaging the primary data over long periods. Such an analysis makes it possible to explain a number of details regarding cosmic ray anisotropy in the minimum of solar activity.

In Figure 32 the mean monthly values of the diurnal variation amplitude are presented in a harmonic diagram from January, 1964, through June, 1965, for the stations Churchill, Deep River and Dallas. Figure 32 shows that in the first quarter of 1964 the phase of the diurnal variation was slightly shifted to an earlier time; other clearly expressed changes are not observed. /44

Figure 33 shows the amplitude and phase values of the solar-diurnal variation during a number of months in 1964 based on the averaged data for five days for the stations Deep River, Dallas and Churchill. These figures indicate that the amplitude varies rather sharply in separate periods, in connection with which synchronous changes in diurnal anisotropy are not observed for the stations (that is, probably local changes in diurnal variation amplitude take place). The phase of the diurnal variation before August, 1964, was shifted to a later time by approximately two hours (from 1400 to 1600 hours local time). This phenomenon is especially noticeable from the data obtained at the middle-latitude station at Dallas.

Let us investigate the change of the solar-diurnal variations from day to day based on the data at the solar activity minimum. The values of the

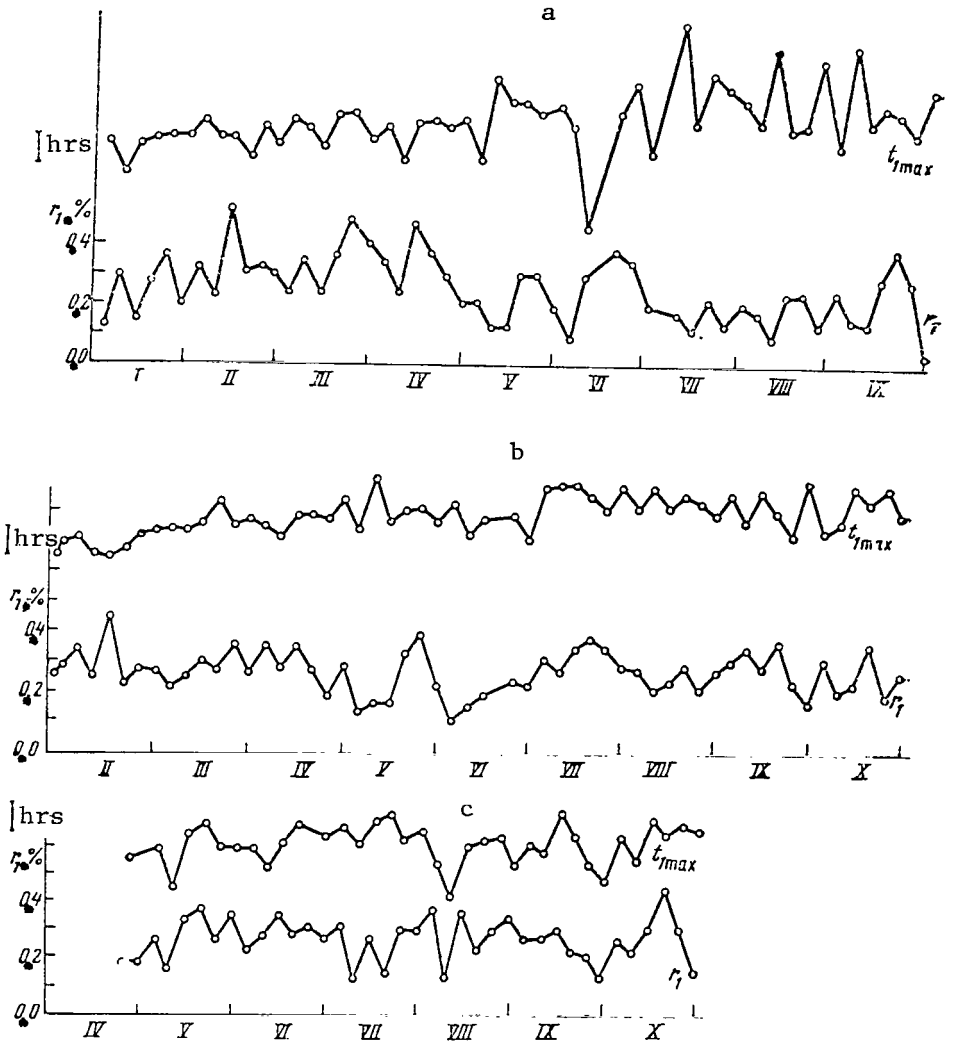


Figure 33. Change in the amplitude r_1 and phase t_{1max} of the diurnal variation in 1964 based on data averaged over five days of observations at the stations: a - Deep River; b - Dallas; c - Churchill.

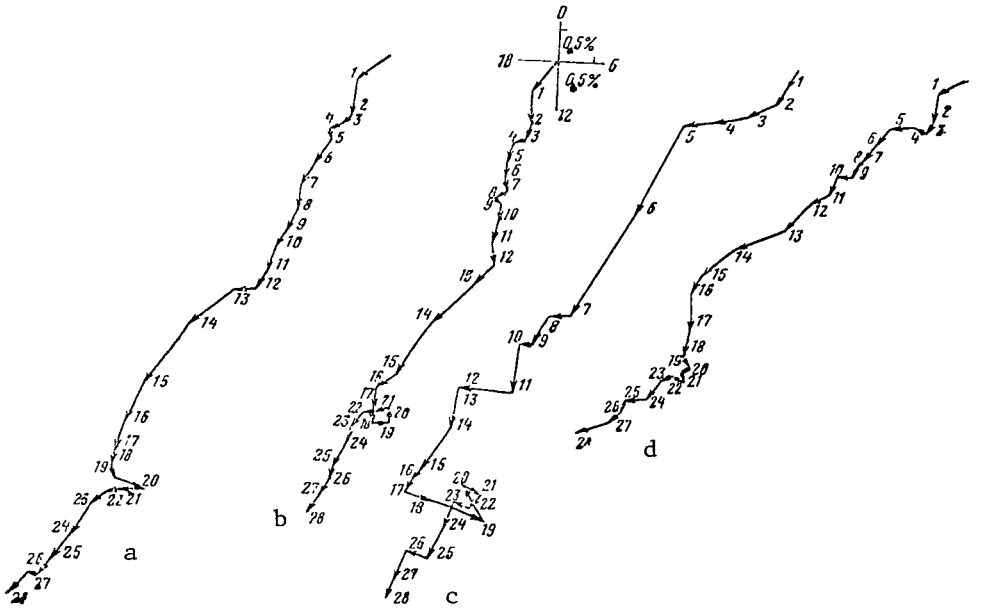


Figure 34. Change in the diurnal variations from day to day in February, 1964, based on observational data at the stations: a - Deep River; b - Dallas; c - Alma-Ata; d - Climax.

diurnal variations during February, 1964, based on data of the stations Alma-Ata, Climax, Dallas and Deep River are presented in Figure 34 as an example. From Figure 34 shows that at all stations a sharp change in diurnal variation phase to a later time occurred on February 3-4, and then a rather sharp change of the phase was also observed at all stations on February 13. Let us note that February 3-4 is a prestorm period (a magnetic storm was observed on February 5 and 13). This is a clear example of the fact that during magnetic storms and Forbush effects the phase is not always shifted to an earlier time (as was customarily assumed). The most interesting case of a solar-diurnal variation change in the intensity of the cosmic ray neutron component occurred in February, 1964 (a deep minimum of the cycle of solar activity) when the vector of the diurnal variation made a complete revolution counterclockwise in six days.

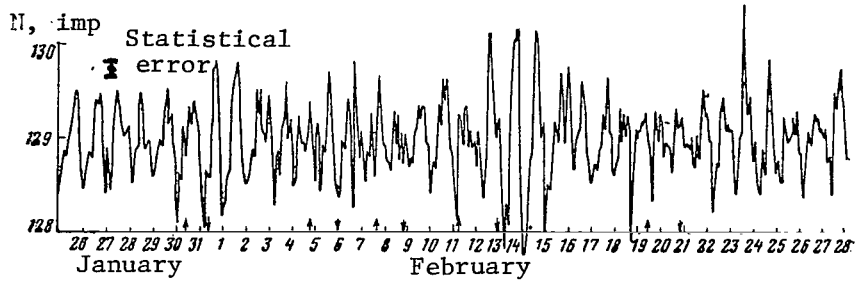


Figure 35. Two-hour values of neutron intensity during the period January 26 - February 28, 1964, based on data of the Dallas station. The data were corrected for barometric pressure and also the variations with a period of intensity change greater than a day were eliminated by the moving averages method.

Figure 34 shows that already on February 16-17 the time of the diurnal variation maximum began to be shifted to earlier hours, and on February 24 at Alma-Ata and Dallas stations (a low geomagnetic latitude) the vector of the diurnal variation described a circle counter-clockwise. At Deep River and Climax stations, the diurnal variation vector either went around a circle at a high speed (during a day) or was shifted by 180° and then returned to the normal position (approximately 1400 hours local time).

For the purpose of representing the manner in which the intensity of the cosmic rays changed in this period, the intensity values of the cosmic ray neutron component are presented in Figure 35 from January 26 through February 28, 1964. The values were obtained by means of a neutron super-monitor set up at Dallas.

On the graph, time is plotted along the abscissa axis, and two-hour values of the intensity of the neutrons are plotted along the ordinate axis. The data were corrected for the barometric effect, and by using the moving method averages [1] the 27-day and eleven-year variations in the cosmic

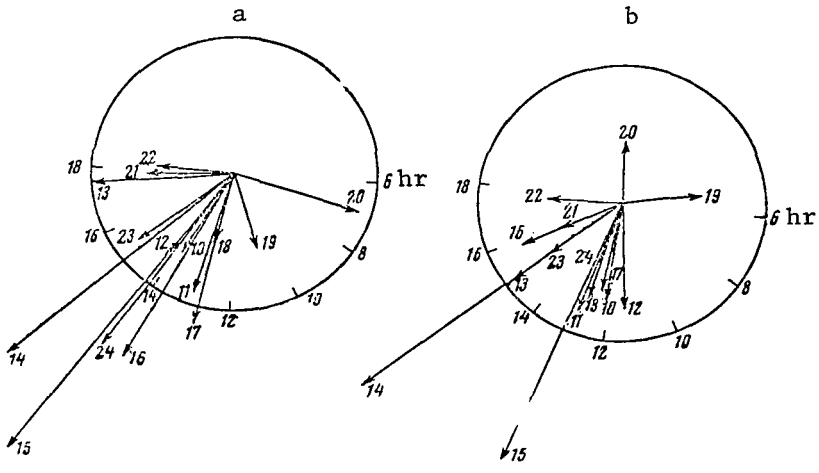


Figure 36. Vector values of the diurnal variation during the period February 11-24, 1964, based on data of the stations: a - Deep River; b - Dallas; the numbers on the vectors are the dates.

ray intensity were eliminated. Also all other variations with a period longer than a day were eliminated. A moderate magnetic storm occurred on January 31, 1964; all the later storms were small [75]. /45

In Figure 35 the solar-diurnal variation is clearly expressed, as a rule increasing after the commencement of a magnetic storm.

The behavior of the diurnal variation vectors on the diagram of a clock dial is shown in Figure 36. One may notice that, for example, at Dallas each day the vector is displaced on the average by six hours. At other stations, the rate of rotation varies from day to day.

In a number of works [76-80] it was shown that during magnetic storms the diurnal variation vector increases and is shifted to an earlier time in a four-hour range. This phenomenon was explained by the earth's capture of a corpuscular stream carrying a "frozen-in" magnetic field, which was confirmed by a general lessening of the cosmic ray intensity at this time. In the given

case, the rotation of the vector began when there was no magnetic storm. A small magnetic storm (the H-component of the earth's magnetic field decreased at the latitude of Alma-Ata by 25-30 gamma) suddenly took place on February 20, but no noticeable intensity decrease in cosmic rays took place. /46

From Figure 36 shows that the diurnal variation amplitude decreased from February 18. This fact is interesting in that it indicates a change toward a decrease in the interplanetary magnetic field, the presence of which is necessary with any modulating mechanism of the diurnal variations [1, 2, 81, 82].

The field decrease in the azimuthal direction possible is produced by a change in solar wind velocity. The magnetic flux in decreases per unit area with a decrease in solar wind velocity, and in this case we will observe small diurnal variations. The change in solar-diurnal variation phase by 12 hours (the opposite value) may be caused by a change in polarity of the interplanetary magnetic field. But if the interplanetary magnetic field were dependent upon the overall field of the sun, which is observed at the polar caps and which changes every 11 years [83-85], then we would notice a change in the time of the diurnal anisotropy maximum in each opposite solar cycle. Experimental data have not verified this phenomenon during the last 20 years. Probably the magnetic fields which are entrained with the solar corpuscular radiation, which we consider to be interplanetary fields, are local fields of sunspots. As is known, the polarity of these magnetic fields may change, especially with the appearance of the sunspots of a new cycle [86]. Therefore, the rotation of the diurnal variation which is being studied by us may be explained by a change in the polarity of the local magnetic field of a group of sunspots. This occurred on February 13-14, 1965. For the purpose of verifying this assumption, let us calculate the solar wind velocity starting from the data on the correlation between the amplitude of the solar-diurnal variations and the sunspot number. The correlation coefficients were calculated for the coinciding days and shifts of the diurnal variation amplitude toward a delay with respect /47

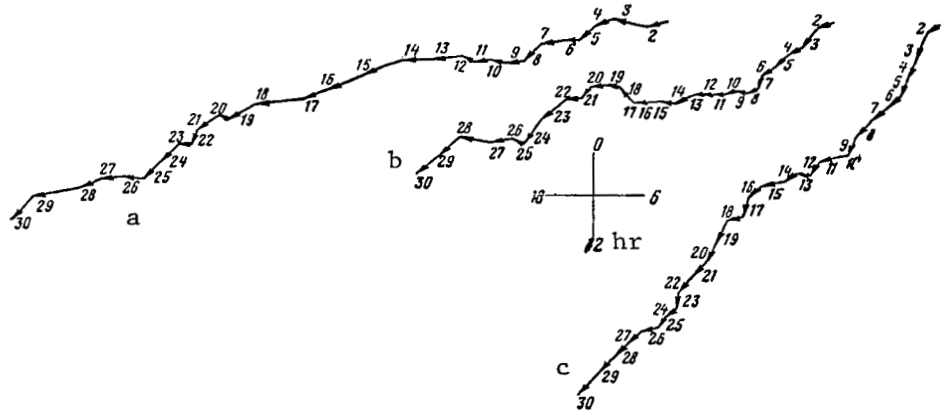


Figure 37. The vector values of the diurnal variations in July, 1964, at the stations: a - Dallas; b - Churchill; c - Deep River.

to the sunspot number. It was found that the greatest positive correlation coefficient (0.7) occurred when the shift equalled five days. Considering this value, let us find the velocity of the solar wind:

$$U = \frac{R_{\odot}}{t} = \frac{1{,}5 \cdot 10^{13}}{5 \cdot 24 \cdot 3600} \simeq 347 \text{ km/sec}$$

The calculated values of the solar wind velocity agree well with the data which were directly measured by satellites and rockets.

Figure 37 presents the diurnal variation vectors calculated for each day of July, 1964, based on data of the stations at Dallas, Churchill and Deep River. From this figure, the phase shift of the diurnal variation from June 9 through June 15, 1964, is clearly seen. In general, in this period, the phase is significantly shifted to a later time (see Figures 32, 34). In this same time (the third quarter of 1964) a solar activity minimum was recorded — based on the sunspot number and the radio-emission at various frequencies.

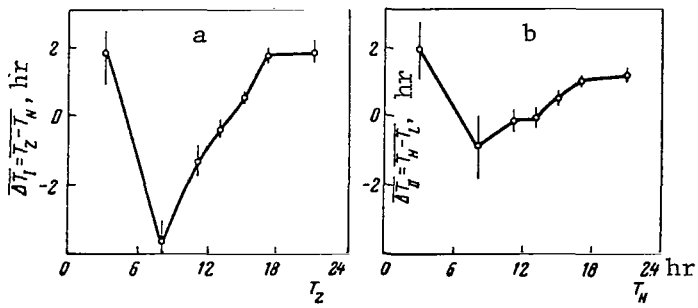


Figure 38. The distribution of ΔT_I using method I (page 34) as a function of time of the maximum at the station Zugspitze (a), and the distribution of ΔT_{II} found using method II as a function of T_H (page 47) (b).

In [66] the authors made a detailed analysis of the diurnal variation phase. In figure 23 the standard deviations are presented as a function of the mean values of ΔT. Thus, with an analysis by means of method I (see Section 5), we obtain $\sigma\Delta T_I$ = 3.5 hr, and according to method II we obtain $\sigma\Delta T_{II}$ = 2.4 hr. /48

One of the reasons for such large differences may be the distortion of the magnetic field by the solar wind.

Figure 38,a shows the average ΔT for seven groups of T (Zugspitze). If the data are separated into groups based on the characteristics of the amplitude ratios, then the average ΔT for each group change in a similar way (Figure 38,b). From an analysis of these data, one may conclude that the average values of ΔT depend not only on the changes in the energy spectrum, but also on the direction of the anisotropy.

The standard deviations in this case, $\sigma'\Delta T_I$ and $\sigma'\Delta T_{II}$, have the values 3.2 and 2.2 hours. Evidently for the majority of changes which are determined by the dependence of ΔT on ΔT_Z (Zugzpitze) the differences between σ and σ' may result from the change in P_{min}.

In [48a, 66], based on the data of the global network of stations recording the neutron components during the IGY period, an analysis was made of the solar-diurnal variations in cosmic ray intensity. In particular, an attempt was made to find the correlation between the phase of the diurnal variation and sunspot number.

The authors of [87] made similar studies based on neutron component data during 1959-1961. Table 17 presents the periods of the study and the number of stations whose data were used in each period. The distributions of the /49
time of the maximum $t_{1\ max}$ in the northern hemisphere are presented in Figure 39 based on the data from observations of the neutron component averaged over each half year. To compare the calculated data of $t_{1\ max}$ during the IGY period and after it with the experimental data, two representative graphs are presented in Figure 40, from which it is seen that in the period after the IGY the distribution of the contours was turned toward the east relative to the IGY period. The contours of t_{1max} obtained after the IGC agree well with the calculated contours of t_{max} obtained with a relatively small number of sunspots ($\leq$ 100).

The dependence of the time of the diurnal variation maximum on sunspot number is described by the expression

$$t_{\max} = a + b \cdot 10^{-2} W,$$

/50

where W is the mean monthly sunspot number. The constant b in this case indicates the rate of change in the time of the diurnal variation maximum. Therefore, it is of interest to see how b changes in the various periods being studied at various points on the earth. The authors of [87] made such an analysis and compared the data for two periods: the first period from January, 1959, through June, 1960; the second period from July, 1960, through December, 1961. The data of the analysis which are presented in Figure 41 show that there is no particularly clearly expressed difference in the various periods. Neither was a difference observed in similar results obtained in the IGY period. Nevertheless, the following tendency is apparent: at

TABLE 17. THE NUMBER OF STATIONS THE DATA FROM WHICH WERE USED IN STUDY [87]

Years	957	1958		1959		196		1961	
Months	7-12	1-6	7-12	1-6	7-12	1-6	7-12	1-6	7-12
Number of stations at sea level	29	34	35	15	15	15	17	17	17
Number of stations at higher elevations	10	11	11	3	3	3	3	3	3
Total number	39	45	46	18	18	18	20	20	20

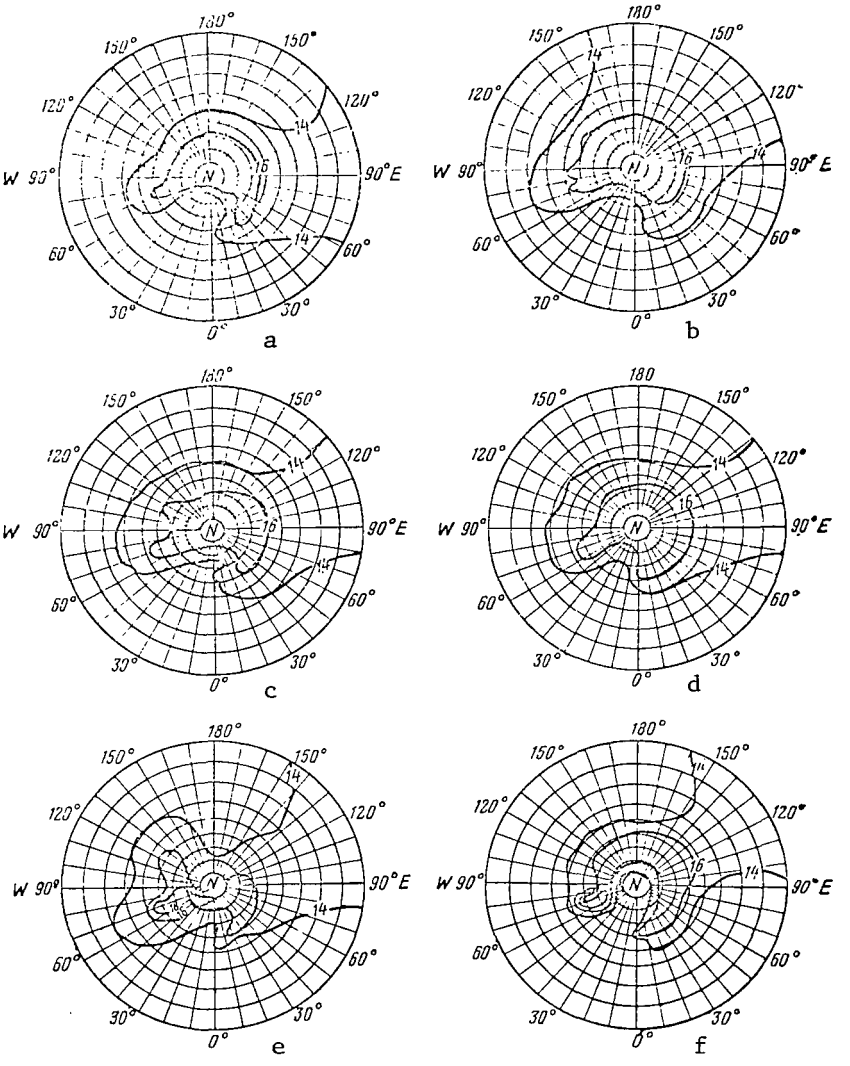


Figure 39. The distribution of t_{1max} (the numbers on the curves are local time) for the neutron component in the northern hemisphere during the periods: a - January-June, 1959; b - July-December, 1959; c - January-June, 1960; d - July-December, 1960; e - January-June, 1961; f-July-December, 1961.

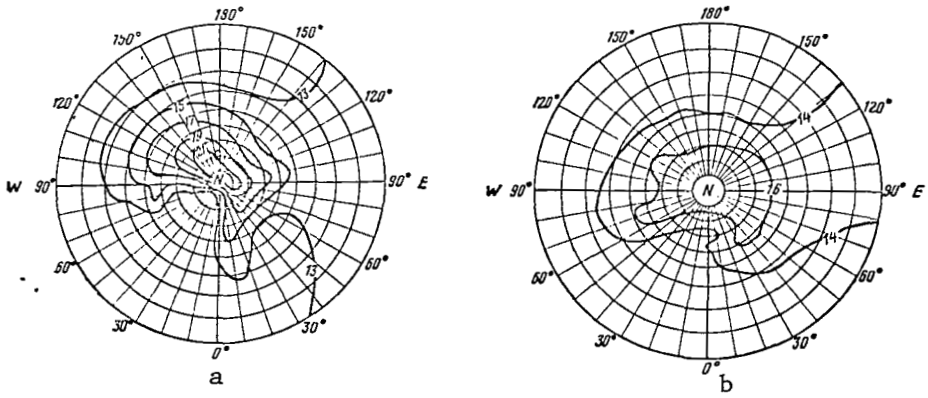


Figure 40. The distribution of t_{1max} (the numbers on the curves are local time) for the neutron component in the Northern Hemisphere during the periods: a - January-June, 1958; b - January-June, 1960.

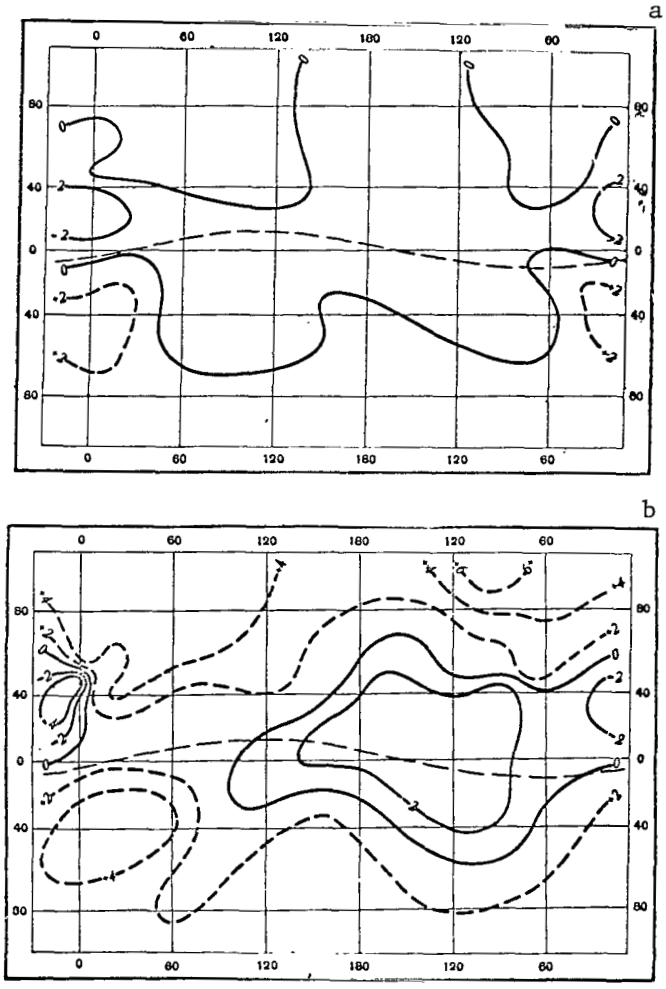


Figure 41. The planetary distribution of the parameter b during the periods: a - January 1959-June 1960; b - July 1960-December 1961.

the lower and middle latitudes $b \leq 0$, which indicates an increase in t_{1max} with an increase in sunspot number. At high-latitude stations and in the South Atlantic region $b \geq 0$, which indicates a shift of t_{1max} to earlier hours with an increase in sunspot number.

10. Solar-Diurnal Variations in Magnetically Disturbed Periods

Let us investigate the results of studying diurnal anisotropy on individual magnetically disturbed days and also in periods of magnetic storms with and without Forbush effects. A study of the diurnal anisotropy in magnetically disturbed periods allows one subsequently to select the anisotropy mechanism which best agrees with the experiment.

Let us note that in the works completed earlier, data were used which were averaged over many magnetic storms. The anisotropy effects may change from case to case, depending on electromagnetic conditions on the sun and in interplanetary space. Therefore, the averaged diurnal effect in individual cases may be significantly smaller in comparison with the anisotropy, or it may entirely disappear. For example, in [41] it was shown that the effect of diurnal variation on the average over a large number of days and separately for quiet days was approximately the same. Let us proceed to an analysis of individual cases. The study was made during three periods: the first before the start of a magnetic storm (averaging over three days); the second during the period of the magnetic storm; the third in the period after the magnetic storm and the Forbush effect.

In Figure 42 [46] data are presented on the first and second harmonics of the diurnal variation of the cosmic ray neutron component during the period of the magnetic storm of July 4-7, 1957, taken from 26 instruments and separated into five latitudinal zones with mean cutoff rigidities of 0.2, 1.5, 3.5, 5.0 and 13.7 BeV (zones I-V), respectively.

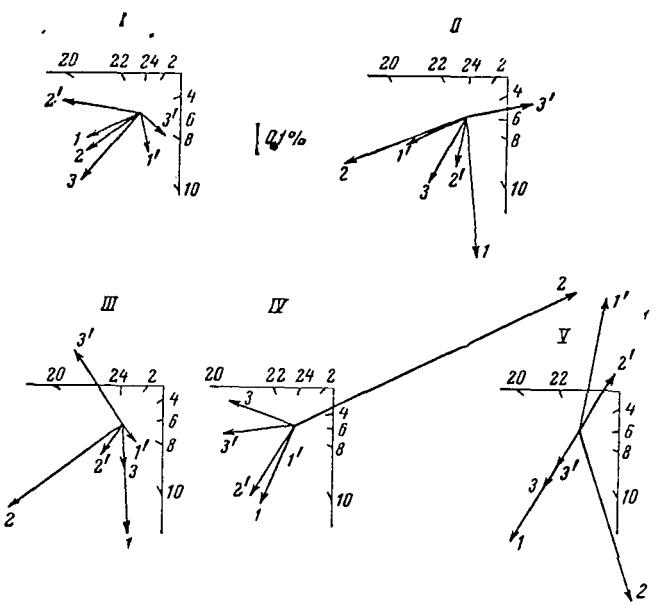


Figure 42. Harmonic diagram for the first harmonic of the diurnal variation of the neutron component of cosmic rays before (1), during (2) and after (3) the magnetic storm of June 4-7, 1957. The vectors also are presented for the semidiurnal variation (1', 2', and 3' respectively for the days before, during and after the magnetic storm). I - the mean rigidity of the geomagnetic cutoff is 0.2 BeV; II - 1.5 BeV; III - 3.5 BeV; IV - 5.0 BeV; V - 13.7 BeV.

Let us designate by 1-3 the first harmonic before the magnetic storm, during the Forbush effect, and after the restoration of the intensity of the cosmic rays; 1', 2' and 3' designate the second harmonic. Figure 42 shows that at the high latitudes the first harmonic remains constant (within the limits of errors) both in amplitude and in phase. The second harmonic after the Forbush effect doubled in amplitude and the phase shifted by four hours to a later time. After the intensity restoration it was decreased by approximately a factor of two, and its amplitude became ∿0.2%. At the lower latitudes (IV, V) the first harmonic increased in amplitude by a factor of two-three, and the phase shifted toward the morning hours. After restoration of the cosmic ray intensity to the normal level, the first harmonic almost disappeared. /51

The second harmonic, especially in the equatorial zone, before the storm was ∿0.5%; after the Forbush effect it decreased to half its value, and the phase shifted to later hours. After the intensity restoration, it decreased to 0.1%.

Figure 43 gives values of the first and second harmonics of the diurnal variation in the neutron component of cosmic rays during the magnetic

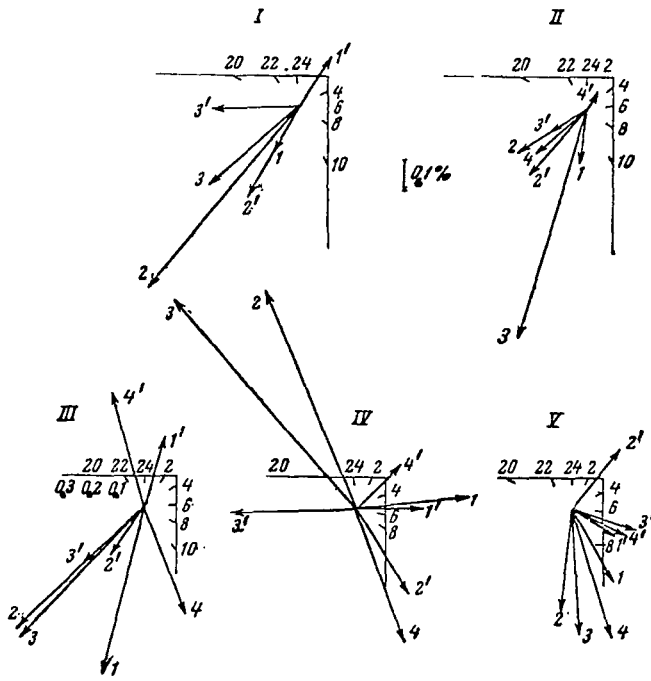


Figure 43. Harmonic diagram of the diurnal and semidiurnal variations for the magnetic storm of August 29, 1957.

1 - before the magnetic storm; 2 - during the magnetic storm; 3 - in the period of the intensity restoration; 4 - after restoration; I - mean cutoff rigidity of 0.15 BeV; II - 1.53 BeV; III - 3.45 BeV; IV - 5.30 BeV; V - 16.0 BeV.

storm of August 29, 1957. The data were averaged over stations divided into latitudinal zones with the following rigidity thresholds: 0.15, 1.53, 3.45, 5.30 and 16.0 BeV. In all zones the first harmonic after the Forbush effect increased in amplitude, and the maximum of the diurnal variation was shifted to later hours. In the period when the intensity of the cosmic rays still was not reestablished to the previous level, after the Forbush effect the amplitude of the diurnal variation at the middle and lower latitudes remained large and the maximum was displaced slightly toward the morning hours. After the intensity restoration the first harmonic in all latitudinal zones except for the second (a mean latitude of 55°) decreased to 0.4 - 0.5%, and the maximum was shifted by approximately eleven hours.

The second harmonic in all the zones increased in amplitude after the Forbush effect, and except for the equatorial zone the maximum was shifted to later hours. After four days, the amplitude decreased and the maximum was displaced to still later hours. After restoration of the cosmic ray intensity, the second harmonic in the latitudinal zone II disappeared, but in the other zones the amplitude remained large and the maximum was displaced to earlier hours.

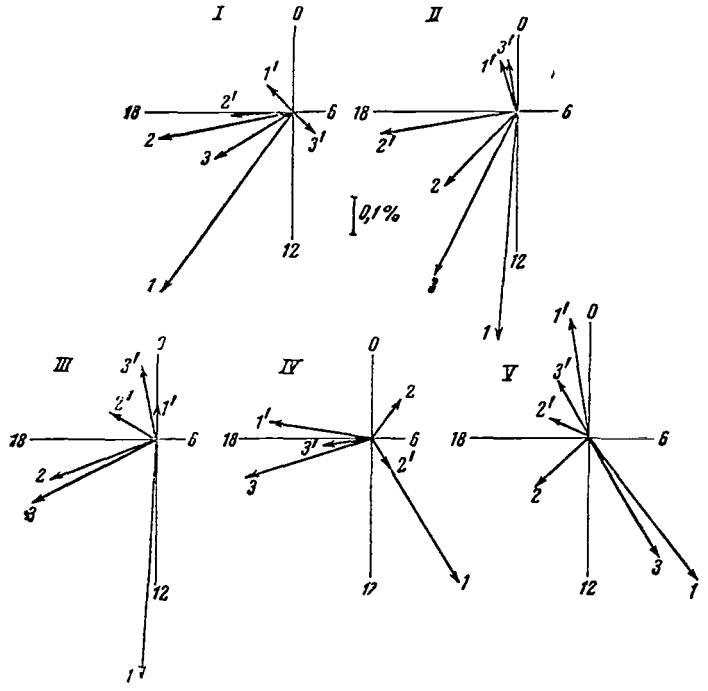


Figure 44. Harmonic diagram for the magnetic storm of September 21, 1957, The designations are the same as in Figure 42; I - for a mean cutoff rigidity of 0.18 BeV; II - 1.45 BeV; III - 3.45 BeV; IV - 5.30 BeV; V - 12.9 BeV.

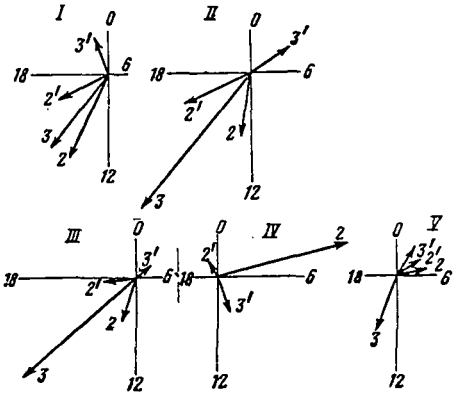


Figure 45. Harmonic diagram for the magnetic storm of September 9, 1957. The designations are the same as in Figure 42.

Figure 44 shows how the phase of the first and second harmonics of the diurnal variat on changed during the magnetic storm of September 21, 1957. Here the data were obtained by averaging over the latitudinal zones of stations with mean rigidity thresholds of 0.18, 1.44, 3.45, 5.30 and 12.9 BeV, respectively, for zones I-V. The data showed that the phase of the first harmonic after the Forbush effect was shifted for zones I-III and V by about four hours to a later time. In zone IV, the phase was shifted by seven hours toward the morning. The phase of the second harmonic was shifted everywhere to earlier hours.

Figure 45 shows how the amplitude and phase of the first and second harmonics change in time for the magnetic storm of September 9, 1957.

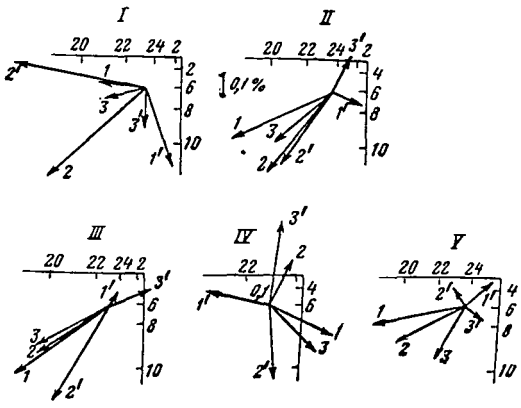


Figure 46. Harmonic diagram for the magnetic storm of October 21-23, 1957. The designations are the same as in Figure 42; I - for a mean cutoff rigidity of 0.15 BeV; II - 1.47 BeV; III - 3.45 BeV; IV - 4.50 BeV; V - 12.8 BeV.

In Figure 46 the first and second harmonics are given before, during, and after the Forbush effect in the period of the magnetic storm of October 21-23, 1957. The figure shows that the first harmonic after the Forbush effect increased at the high latitudes (belt I), remained constant at middle latitudes (zones II-IV), and decreased at low latitudes (zone V). The phase shifted toward the morning hours at all latitudes. After the intensity restoration the amplitude decreased and the phase was shifted to later hours in the latitudes of zones I-IV, but in the equatorial zone (zone V) it was shifted toward the morning hours.

The cutoff rigidity for the belts I-V equalled 0.15, 1.47, 3.45, 4.50 and 12.8 BeV, respectively.

The amplitude of the second harmonic in the high and middle latitudes increased (zones I-III). In zone IV it remained unchanged, but in the equatorial region it decreased. The phase of the second harmonic in zones I-III and V shifted to later hours, but in zone IV it shifted toward the morning hours.

In Figure 47 the first and second harmonics of the diurnal variation in the neutron component of cosmic rays are presented for the magnetic storm of February 11, 1958. The resulting values were obtained from the averaged /54 data for stations located at various points on the earth. The mean rigidity threshold for zones I-V equals 0.14, 1.54, 4.0, 5.3 and 16.0 BeV, respectively.

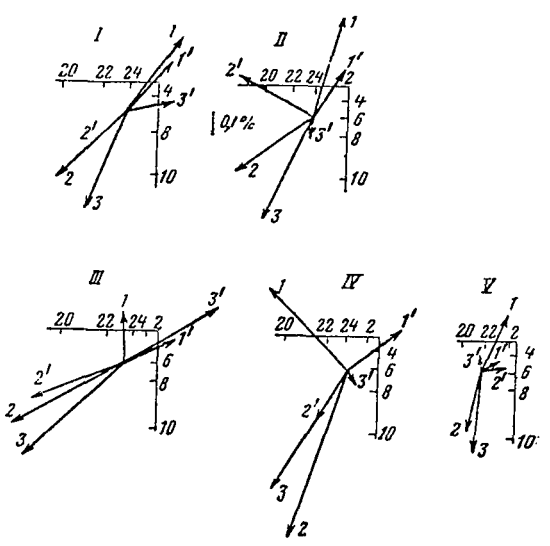


Figure 47. Harmonic diagram of the first and second harmonics during magnetic storm of February 11, 1958.

The designations are the same as in Figure 42; I - for a mean cutoff rigidity of 0.14 BeV; II - 1.54 BeV; III - 4.0 BeV; IV - 5.3 BeV; V - 16.0 BeV.

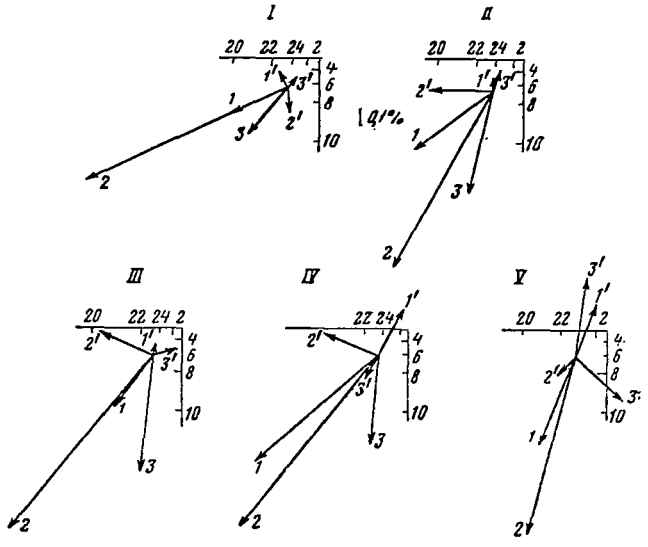


Figure 48. Harmonic diagram for the magnetic storm of May 9, 1958.

The designations are the same as in Figure 42; I - for a mean cutoff rigidity of 0.1 BeV; II - 1.9 BeV; III - 3.6 BeV; IV - 6.3 BeV; V - 12.5 BeV.

Figure 47 shows that the first harmonic at all latitudes increased after the Forbush effect by a factor of one and one-half, and the phase changed very sharply. After the restoration of cosmic ray intensity, the diurnal variation amplitude remained large, and there was almost no change in phase.

The amplitude of the second harmonic after the Forbush effect sharply increased at the high and middle latitudes (zones I-III), it slightly decreased for zone IV, and it was practically absent in the equatorial region. The phase of the second harmonic of the Forbush effect was shifted to a later time.

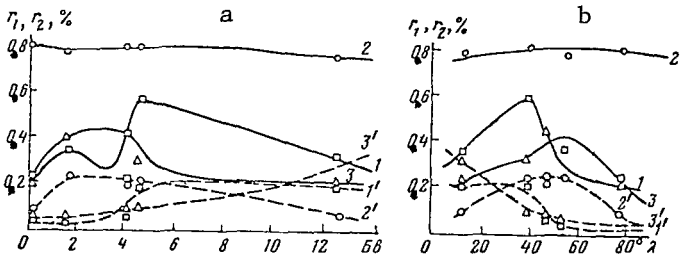


Figure 49. Amplitude of the diurnal variation as a function of cutoff rigidity (a) and geomagnetic latitude (b) based on data of observations during the magnetic storm of May 9, 1968.

1 - before the intensity restoration for the first harmonic; 2 - the first harmonic during the intensity restoration; 3 - the first harmonic after the intensity restoration; 1', 2' and 3' - the same for the second harmonic.

In Figure 48 the change of the diurnal and semidiurnal variations is shown in harmonic diagrams before the Forbush effect, during the magnetic storm of May 9, 1958, after the effect, and when the intensity of the cosmic rays was restored to the level of the undisturbed period. The stations recording the neutron component of cosmic rays were separated into groups with mean rigidity thresholds of 0.1, 1.9, 3.6, 6.3 and 12.5 BeV, respectively, for the zones I-V.

In Figure 49 the amplitude of the diurnal and semidiurnal variations is given as a function of the cutoff rigidity and as a function of geomagnetic latitude during the magnetic storm of May 9, 1958. The figure shows that the amplitude of the first harmonic after the Forbush effect increased by a factor of 2-2.5, and was the same ($\sim$ 0.8%) at all latitudes. Before the Forbush effect and after the restoration of cosmic ray intensity to the normal level, the amplitude of the diurnal variation was greatest at a geomagnetic latitude of 30 - 50°, and decreased with transition to high and low latitudes.

The amplitude of the semidiurnal variation after the Forbush effect had a maximum at the middle latitudes (35 - 55°) and decreased with transition to low and high latitudes. Before the Forbush effect and after the intensity restoration, the amplitude had a maximum value at the low latitudes and decreased with a transition to higher latitudes.

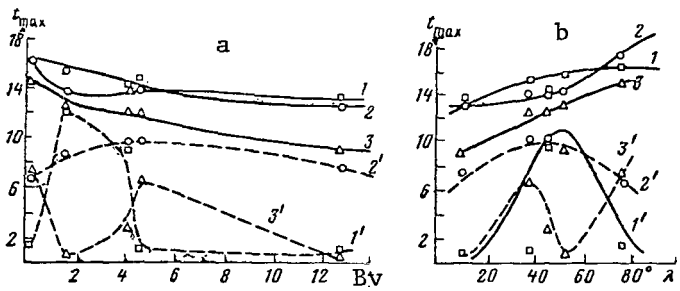


Figure 50. Phase of the first and second harmonics of the diurnal variation as a function of cutoff rigidity (a, b) for the magnetic storm of May 9, 1958.

The designations are the same as in Figure 49.

In Figure 50 the change in the diurnal and semidiurnal variation phases is presented as a function of cutoff energy and geomagnetic latitude. The figure shows that the time of the diurnal variation maximum in all cases was shifted to earlier hours with an increase in the cutoff energy. Accordingly, after the intensity of the cosmic rays was restored to the normal level, the time of the maximum at all latitudes also was shifted to earlier hours.

In the second harmonic, the time of the maximum at low and high latitudes was shifted to later hours; in the middle latitudes it remained unchanged.

In Figure 51 the values of the first and second harmonics of the diurnal variation are shown in a harmonic diagram before and after the Forbush effect occurring during the magnetic storm of May 26-30, 1958 and after the restoration of cosmic ray intensity to the normal level (the level before the Forbush effect). The figure shows that the amplitude of the first harmonic after the Forbush effect in the zones I and II (cutoff rigidity of 0.14 and 1.54 BeV) increased by a factor of two, and its phase was displaced toward the morning hours.

For zone III (cutoff rigidity of 4 BeV) the amplitude of the first harmonic increased by a factor of two, and the time of the maximum was shifted to later hours. For zone IV a diurnal variation was absent before the Forbush effect, but immediately after it increased to ∿0.4%. For stations in the equatorial zone, the diurnal variation decreased in amplitude,

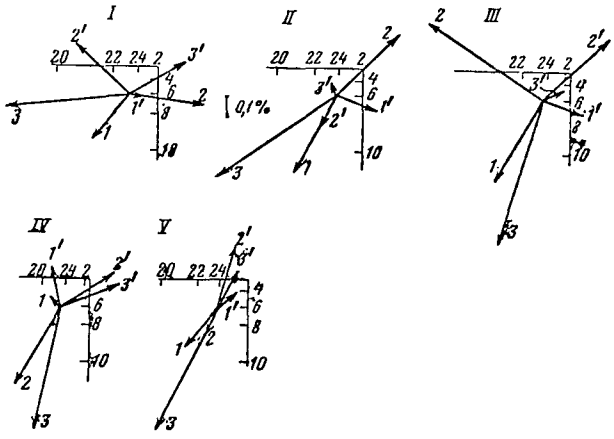


Figure 51. Harmonic diagram for the magnetic storm of May 26-30, 1958.

The designations are the same as in Figure 42.

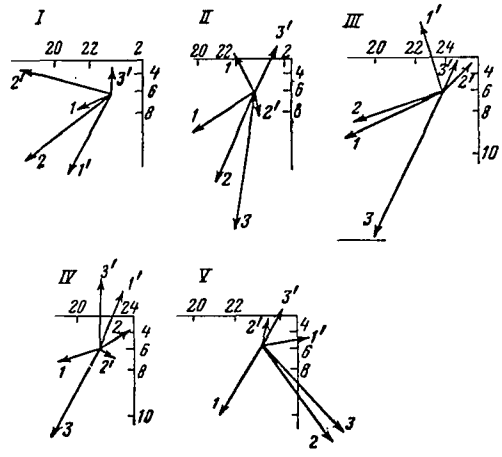


Figure 52. Harmonic diagram for the magnetic storm of October 22-25, 1958.

The designations are the same as in Figure 42.

and the phase was displaced toward an earlier time. After the restoration of the cosmic ray intensity the diurnal variation at all latitudes sharply increased and the time of the maximum was displaced toward the morning hours.

In Figure 52 the data of the first and second harmonics of the diurnal variation during the magnetic storm of October 22-25, 1958 are presented. The /56 first harmonic for zones I, II and IV increased by a factor of two, and the maximum was shifted to earlier hours. In zone III the amplitude and phase of the first harmonic remained unchanged. In zone IV the amplitude of the first harmonic was not changed, but the phase was shifted toward the morning hours. After the intensity restoration, the first harmonic in zone I disappeared. In zones II and III it increased by a factor of one and one-half and the phase shifted to earlier hours. In zone IV the first harmonic increased by a factor of two and the phase was shifted to an earlier time. In zone V, both the amplitude and the phase of the first harmonic remained unchanged.

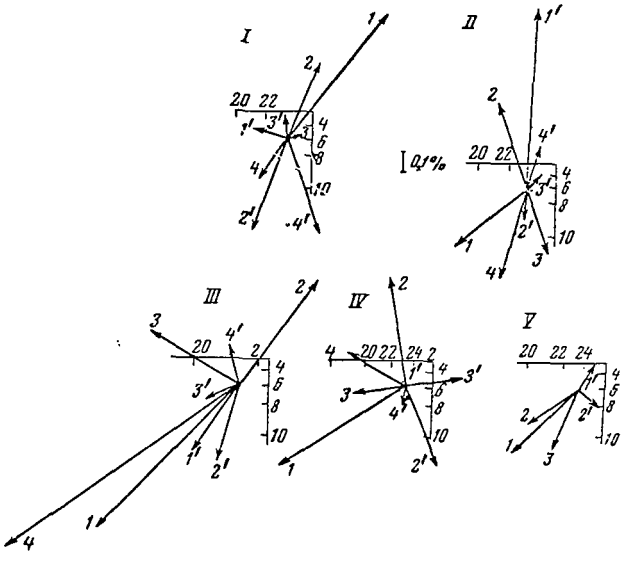


Figure 53. Harmonic diagram for the magnetic storm of February 11-17, 1959.

The designations are the same as in Figure 42.

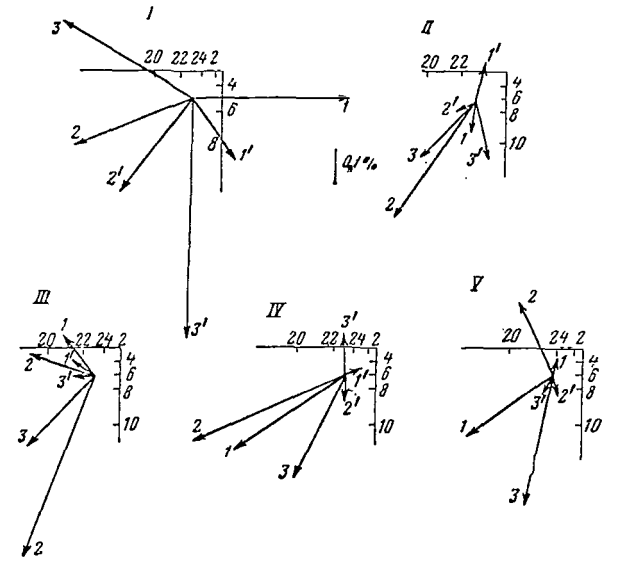


Figure 54. Harmonic diagram for the magnetic storm of March 26-31, 1959.

The designations are the same as in Figure 42.

Figure 53 shows that a strong change both in amplitude and phase of the first and second harmonics of the diurnal variation of the neutron component intensity of cosmic rays took place during the magnetic storm of February 11-17, 1959. The amplitude of the first harmonic decreased in all five zones after the main phase of the magnetic storm. The phase in zones I and II was shifted toward the morning hours, and in zones II, IV and V it was shifted toward a later time. One should note that in all cases represented in Figures 51-54 the second harmonic changed sharply both in amplitude and in phase.

In Figure 54 data on the diurnal and semidiurnal harmonics are presented before, during, and after the Forbush effect during the magnetic storm of March 26-31, 1959. The figure shows that the amplitude of the first harmonic after the main phase of the magnetic storm in zones I and V

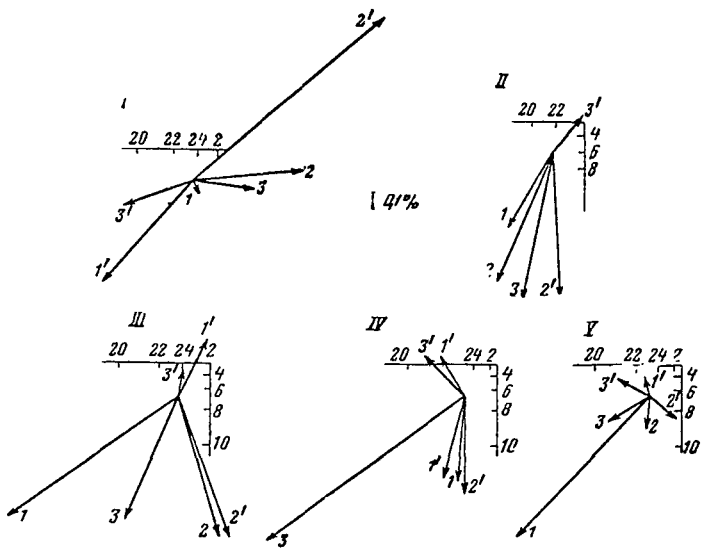


Figure 55. Harmonic diagram for the magnetic storm of May 11-13, 1959.

The designations are the same as in Figure 42.

remains constant, but the phase was shifted to a later time. In zones II-IV, the amplitude of the first harmonic increased, but the phase in zones II and IV was shifted by one hour to a later time. In zone III it shifted by one hour to earlier hours.

The second harmonic at high latitudes (zone I) reached a large value after the restoration of the cosmic ray intensity to the normal level. In the equatorial zone and in the low latitudes, the second harmonic was practically absent.

After the main phase of the magnetic storm of May 11-13, 1959, the first harmonic of the diurnal variation in zones I-III and V sharply increased, but in zone IV it remained constant (Figure 55). The phase of the second harmonic in zones I and IV shifted to earlier hours but in zones II, III and V it shifted to later hours.

In Figure 56 the amplitudes of the first and second harmonics of the diurnal variation averaged over nine cases are presented as a function of the cutoff rigidity and geomagnetic latitude. The data were averaged over the following Forbush effects: June 4, October 21, 1957; February 11, May 9 and 26, October 22, 1958; March 26, April 3 and May 11, 1959. Figure 56 shows that the amplitude of the first harmonic after the main phase of the magnetic storm slightly increased in the middle latitudes, but at high and low latitudes it remained constant. The amplitude of the second harmonic during all periods of the Forbush effect remained unchanged, and at high latitudes it was large. /58

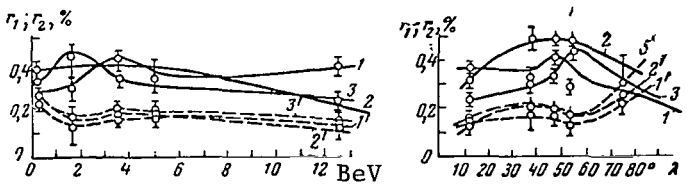


Figure 56. Amplitude of the first and second harmonics of diurnal variation as a function of cutoff rigidity (a) and as a function of geomagnetic latitude (b). The data were averaged over the periods of nine magnetic storms.

The designations are the same as in Figure 49.

In Figure 57 the behavior of the phase of the first and second harmonics is given as a function of cutoff rigidity and geomagnetic latitude. The figure shows that for both the first and the second harmonic the time of the maximum is shifted to earlier hours with an increase of the cutoff rigidity or with a decrease in geomagnetic latitude.

From Figure 58 [88] it is seen that during a magnetic storm the amplitude of the diurnal variation increased by a factor of two or more, and the time of the maximum shifted to earlier hours.

An analysis of the diurnal and semidiurnal variations based on data for three days before the Forbush effect occurring on June 8, 1958 [89] and the three days after the Forbush effect — averaged for five instruments located in the southern hemisphere and 20 instruments located in the northern hemisphere — showed that an additional diurnal variation is especially noticeable in the southern hemisphere and is somewhat reduced in the northern hemisphere. It is necessary to point out that in this case one may talk only about a tendency to an increase or a decrease in diurnal variation. The semidiurnal variation during the storm evidently increased both in the northern and in the southern hemispheres (Table 18).

The time of the maximum of the first harmonic at all stations was shifted toward the morning hours. The time of the second harmonic at thirteen stations was shifted toward the evening hours, and at the remaining stations it was shifted toward the morning hours. In Figure 59 the first

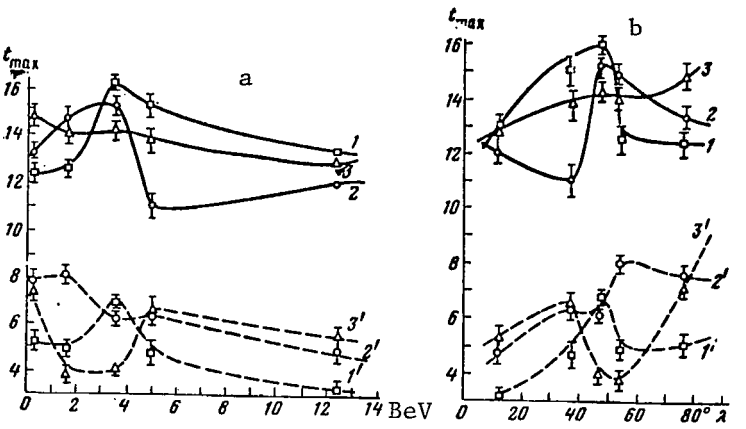


Figure 57. Phase of the first and second harmonics as a function of the cutoff rigidity (a) and as a function of geomagnetic latitude (b) based on the same data used in Figure 56.

The designations are the same as in Figure 49.

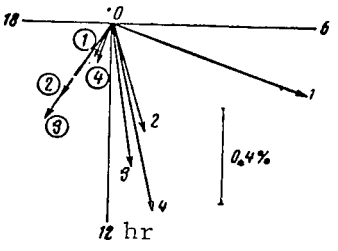


Figure 58. Harmonic diagram of the first harmonics of the diurnal variation before and during the magnetic storm of March 25, 1958 based on the data for the stations:

1 - Huancayo; 2 - Hermanus; 3 - Wiesenau; 4 - Ottawa; the data which refer to the disturbed period are surrounded by small circles.

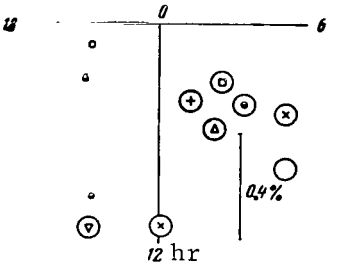


Figure 59. First harmonic of the diurnal variation based on the data of the neutron component at various stations during the time of the magnetic storm of June 8, 1958.

The data referring to the disturbed period are enclosed by small circles.

TABLE 18. CHANGE IN THE DIURNAL VARIATION IN THE FORBUSH EFFECT PERIOD

Hemisphere	Before the Forbush effect, amplitude in %		After the Forbush effect, amplitude in %	
	First harmonic	Second harmonic	First harmonic	Second harmonic
Southern	0.49±0.07	0.27±0.05	0.53±0.07	0.33±0.05
Northern	0.56±0.03	0.24±0.02	0.52±0.03	0.34±0.02

harmonic of the diurnal variations for certain stations is shown on the basis of the data before and during a storm.

Let us investigate the interesting case of the disturbed diurnal variation in the period October 21 - November 2, 1959 [90]. In Figure 60 the values of the neutron intensity and the horizontal component of the earth's magnetic field are presented for the indicated period. For the purpose of studying this case, the registered data from 23 neutron monitors were used. In Figure 61 the amplitude of the first and second harmonics is presented as a function of the cutoff rigidity for the periods I-V, respectively. Figure 61 shows that the amplitude of the diurnal variation on the quiet days of October 21-22 reached 0.2-0.8% for the high-latitude stations, and 0.2-0.4% for the low-latitude stations. The amplitude of the semidiurnal variations on these days fluctuated from 0.1 to 0.5% for all latitudes (Figure 61). The time of the diurnal variation maximum on these days was in the range 1200-1600 hours local time for all stations (Figure 61a, I).

An analysis of the diurnal variation for October 27 (Figure 61) showed that the amplitude increased by approximately a factor of two;

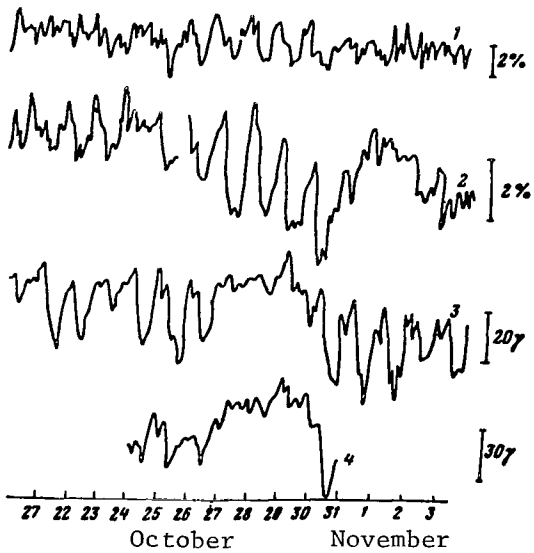


Figure 60. The values of the intensity of neutrons (1 and 2) and the H-component of the earth's magnetic field (3 and 4) based on the data of the stations:

1 - Buenos Aires; 2 - Deep River; 3 - Kobenul (Vienna); 4 - Kakioka.

at the high-latitude stations it was ∿2%, and at the low-latitude stations it was ∿1%. The amplitude of the semidiurnal variation on this day also increased by approximately a factor of two in comparison with the quiet days October 21-22, and also a decrease in amplitude was observed with a decrease in latitude (Figure 61). The time of the diurnal variation maximum fluctuated from 14 to 20 hours for the high-latitude stations, and did not exceed 14 hours for the low-latitude stations (see Figure 62a, II in which the latitude dependence is seen). /62

The time of the semidiurnal variation maximum fluctuated from 1 to 11 hours for all latitudes (Figure 62b, II).

No clear dependence of the time of the maximum on the cutoff rigidity for the second harmonic of October 27 is observed, as is seen from Figure 62b, II. Thus the picture of the dependence of the time of the maximum for the semidiurnal variation of October 27 remained unchanged in comparison with the quiet days October 21-22.

Now let us investigate the next period of disturbances — October 28. From Figure 61,a, III it is seen that the amplitude of the diurnal variation remains the same as that on October 27, that is, 2.0-2.2%. As previously, a tendency is observed toward a decrease in amplitude with a decrease in latitude. The amplitude of the semidiurnal variation (Figure 61b, III) also remained unchanged in comparison with the same

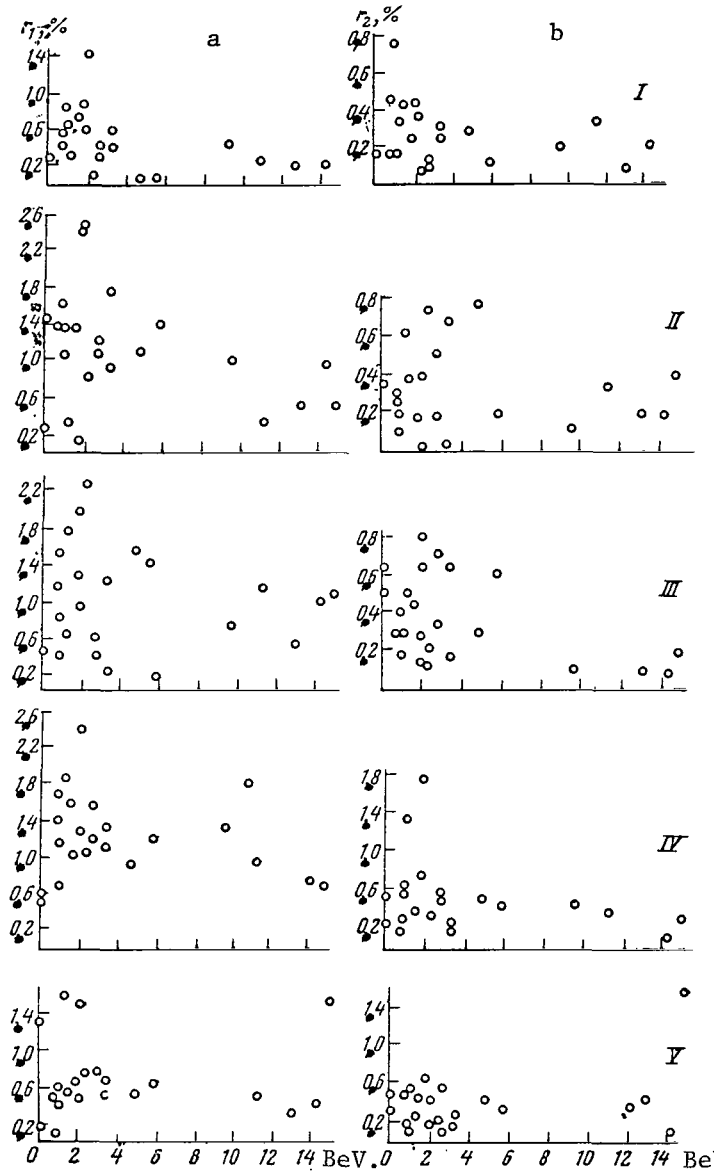


Figure 61. Amplitude of the first harmonic (a) and second harmonic (b) as a function of cutoff rigidity:

I - averaged data for October 21-22; II, III, IV - disturbed days separately for October 27, 28 and 29; V - averaged data for November 1 and 2, 1959.

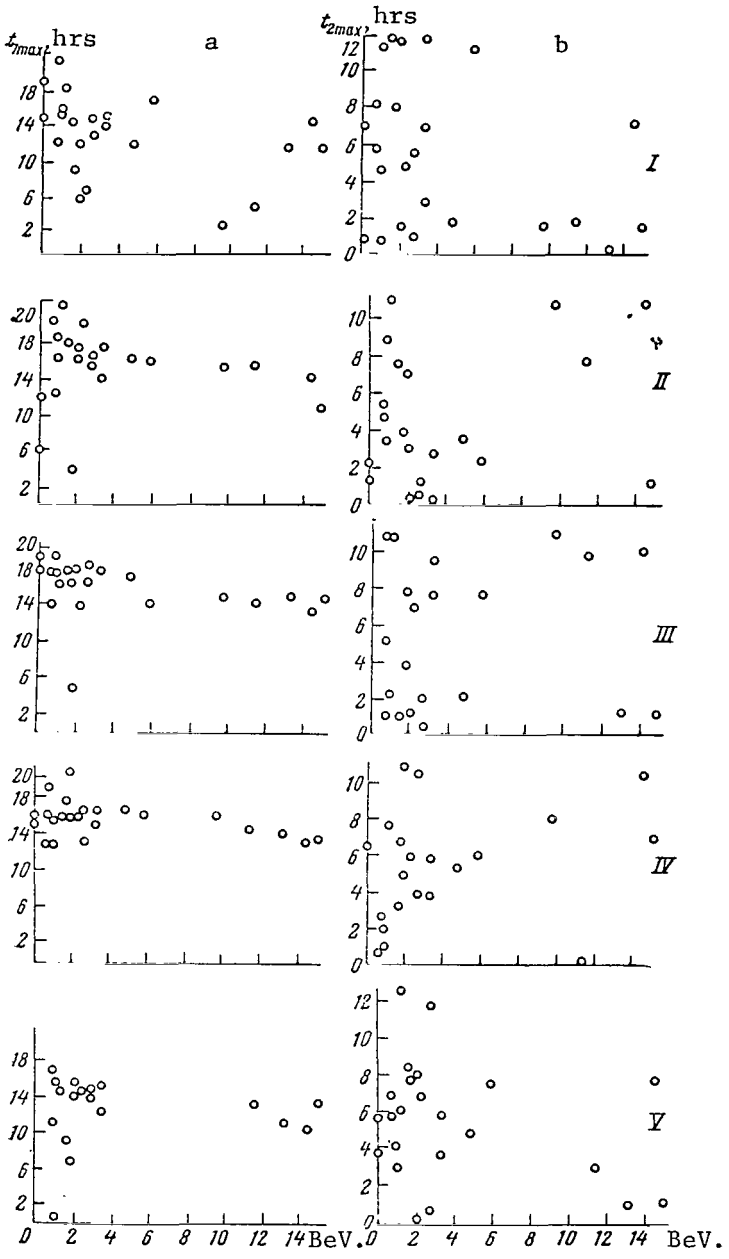


Figure 62. The time of the maximum of the first harmonic (a) and the second harmonic (b) as a function of cutoff rigidity.

The designations are the same as for Figure 61

*Translater's note: commas appear as decimal points.

amplitude which was observed on October 27, that is, ∿0.7%. The time of the maximum for the first harmonic (Figure 62,a, III) of October 28 for the majority of the stations was shifted by one hour to later hours in comparison with October 27. As previously, a shift of the maximum was observed toward earlier hours with a decrease in latitude. A clear dependence of the time of the maximum for the semidiurnal variation on the cutoff rigidity on October 28 was not observed (Figure 62,b, III). The time of the maximum fluctuated for various stations from 1 to 11 hours. A dependence of the diurnal variation amplitude on longitude in the limits 0-20°E was noted, and a high amplitude (up to 2.4%) was observed. Also there was a tendency toward a reduction of the amplitude with the transition from western to eastern longitudes.

The magnitude of the second harmonic amplitude remained the same as on October 27 although at 3-4 stations a large amplitude (0.6-1.0%) was observed (there was no clear dependence on longitude, but there was a tendency toward a reduction in amplitude with transition from western to eastern longitudes).

The time of the maximum for the first harmonic of October 28 for the majority of stations is between 14-18 hours, and only for three stations did it change from 20 to 22 hours in the eastern and western hemispheres. The time of the maximum was approximately the same for all stations, and did not depend on the longitude.

For the semidiurnal variation, the time of the maximum in the western hemisphere was between 2-11 hours, and in the eastern hemisphere between 1-7 hours. With transition to larger eastern longitudes, a tendency was observed toward a decrease in time of the maximum.

As is seen from Figure 61a, IV a clear latitude dependence for the amplitude of the diurnal variation is observed on October 29. Accordingly, the amplitude for the high-latitude stations was 0.6-1.8%, and for

the low-latitude stations it was 0.8-1.2%. Consequently, the amplitude remained the same as on the preceding disturbed days October 27-28 in

The amplitude of the semidiurnal variation of October 29 also barely changed for almost all the stations and was 0.2-0.7% (Figure 61,b, IV). The amplitude of the second harmonic sharply increased to 1.3-1.7% only for two stations. A reduction in amplitude also was observed with a decrease in latitude. The time of the maximum of October 29 changed from 13 to 20 hours for all stations (Figure 62,b, IV). A shift of the time of the maximum was observed toward earlier hours with a decrease in latitude (as also was the case on October 27-28).

Figure 62,b, IV shows that, as previously, no clear latitude dependence is observed for the time of the second harmonic maximum. The time of the maximum fluctuates for various stations from ∿1 to 11 hours. The magnitude of the amplitude for the diurnal variation of October 29, as is seen from the figure, remains the same as on the preceding disturbed days of October 27-28. Accordingly, the amplitudes in the western and eastern hemisphere were approximately the same (the same is true for the semidiurnal variation).

The time of the maximum for the first harmonic of October 29, the same as for October 27-28, was reached at 13-20 hours for all stations, although on October 29 with transition from the western to the eastern hemisphere, the time of the maximum tended to shift by ∿1 hours to later hours. /65

The time of the maximum for the second harmonic of October 29 in the western hemisphere remained unchanged, whereas in the eastern hemisphere it was shifted to later hours by approximately 3 hours for all longitudes in comparison with the preceding disturbed days October 27-29. Finally let us investigate the last quiet period — the data averaged over November 1-2.

From Figure 61, a shows that the amplitude of the diurnal variation decreased by approximately a factor of two in comparison with the disturbed

days October 27-29 and reached 0.4-0.8% for the high-latitude stations and 0.4-0.5% for the low-latitude stations (except for three stations where the amplitude reached a large value of 1.4-1.6%).

The amplitude of the semidiurnal variation of November 1-2 also decreased to 0.1-0.5% for all stations, that is, by approximately a factor of one and one-half in comparison with the disturbed days October 27-29. It is impossible to say anything here about the latitude dependence (Figure 61,b).

The time of the diurnal variation maximum (Figure 62,a,V) for the majority of stations on November 1-2 was shifted by 2-3 hours to earlier hours (0800-1600 hours) except for the two high-latitude stations where the time of the maximum was ∿2100-2200 hours. A small reduction in the time of the maximum with latitude was observed. The time of the maximum of the second harmonic (Figure 62, b, V) was shifted by 2-3 hours to earlier hours at the low-latitude stations.

A tendency was observed towards an increase in amplitude from the western longitudes to the larger eastern longitudes.

With respect to the amplitude of the semidiurnal variation, one can say that there is no clear dependence on longitude. The amplitude of the semidiurnal variation remained the same (∿0.1-0.5%) as on the disturbed days.

An analysis of the amplitude distribution of the first and second harmonics (obtained after averaging the data along the zones separately for the northern and southern hemispheres) gives interesting results. In Table 19 the results of the averaging are presented: a — based on the data of the northern high-latitude stations, b — based on the northern low-latitude stations, c — based on the southern high-latitude stations, d — based on the southern low-latitude stations. Table 19 shows (from a comparison of r_1 for the group of stations a and c) that in periods I and II the additional diurnal variation in the northern hemisphere at the high latitudes

TABLE 19. AMPLITUDE OF THE FIRST HARMONIC (r_1 in %) AND THE SECOND HARMONIC (r_2 in %) OVER THE LATITUDE GROUPS OF STATIONS a-d IN THE PERIODS I-V

Group of stations	Periods									
	I		II		III		IV		V	
	r_1	r_2	r_1	r_2	r_1	r_2	r_1	r_2	r_1	r_2
a	0,627	0,313	1,414	0,288	1,260	0,396	1,078	0,404	0,535	0,352
b	0,276	0,197	0,663	0,308	0,966	0,227	0,946	0,370	1,073	0,348
c	0,382	0,288	0,435	0,422	0,905	0,290	1,155	0,545	0,758	0,368
d	0,171	0,222	1,028	0,236	0,882	0,364	1,170	0,545	0,418	0,225

was three times larger than in the southern hemisphere. This indicates that the field in the stream was parallel to the plane of the ecliptic and directed opposite to the earth's rotation around the sun.

Now let us investigate the additional diurnal variations for period III. Table 19 shows that here the situation was the same as in periods I and II, but the amplitude difference was substantially smaller. For periods IV and V the amplitude of the diurnal variations in the southern hemisphere was already slightly larger than in the northern hemisphere. This indicates that the field in the stream changed to the opposite direction. One should note that the amplitude ratio for the low-latitude stations is opposite. /66

For the second harmonic no definite pattern is observed. For example, whereas for period I at the high latitudes the amplitude in the northern and southern hemispheres was larger than at the low latitudes, for period II in the northern hemisphere the amplitude of the second harmonic is the same at the high and low latitudes. However, in the southern hemisphere at the high latitudes the amplitude is two times larger than at low latitudes. In period III the pattern is the reverse of Period II. In period IV the amplitude of the second harmonic in the southern

TABLE 20. THE TIME OF THE MAXIMUM OF THE FIRST HARMONIC ($t_{1\ max}$) AND THE SECOND HARMONIC ($t_{2\ max}$) OVER THE LONGITUDE GROUPS a-e IN THE PERIODS I-V

Group of stations	Periods									
	I		II		III		IV		V	
	$t_{1\ max}$	$t_{2\ max}$	$t_{1\ max}$	$t_{2\ max}$	$t_{1\ max}$	$t_{2\ max}$	$t_{1\ max}$	$t_{2\ max}$	$t_{1\ max}$	$t_{2\ max}$
a	10,5	3,1	13,9	6,9	15,0	9,2	14,1	3,6	11,9	4,0
b	14,4	6,2	16,5	4,8	16,3	6,2	14,2	2,2	9,1	5,4
c	14,1	5,1	16,1	6,2	15,1	5,9	14,4	4,3	13,2	4,3
d	10,0	4,6	16,9	6,8	16,3	3,8	16,3	8,1	15,1	8,8
e	12,7	6,2	14,3	4,6	16,4	3,2	16,5	5,6	14,8	4,9

hemisphere at all latitudes was larger than in the northern hemisphere. In period V only at the low latitudes of the southern hemisphere was the amplitude decreased; at the remaining latitudes the amplitude was the same (the statistical error in determining the amplitudes of the first and second harmonics in all cases did not exceed 0.1%).

Now let us proceed to an investigation of the time of the maximum of the diurnal and semidiurnal variations in the neutron component intensity of the cosmic rays (Table 20).

In this table the groups for averaging were selected on the basis of the longitudinal criteria: a — the stations located in the southern hemisphere at longitudes from 58 to 75° W; b — stations located in the northern hemisphere at longitudes from 70 to 115° W; c — stations located in the southern and northern hemispheres at longitudes from 50 to 150° W; d — averaged for the stations located in the eastern hemisphere (longitudes 137-168° E); e — stations located in the eastern hemisphere (longitudes 0.4-76° E).

Table 20 shows that the time of the maximum of the diurnal variation in periods II and III is shifted over the entire earth to later hours relative to period I. In period IV, in the western hemisphere a shift was recorded to earlier hours, but in the eastern hemisphere this shift began only in period V.

No definite relationship was observed in the change of the time of the second harmonic maximum.

The numerous results presented above on processing the experimental data based on the global network of stations indicate an exceptional complexity of the phenomena being investigated. In each specific case, distinctive features in the change of the cosmic ray anisotropy are observed. From this it follows that, for studying the electromagnetic conditions in the earth's vicinity Earth, it is necessary to investigate individual cases. The averaging of data over many cases may lead to a loss of a number of interesting details.

However, the data described above from many magnetic storms show that there also are general patterns in the change in intensity of cosmic rays: /67

1) The time of the maximum of the diurnal variation first harmonic tends to shift to evening hours with transition from large to small rigidities (from low geomagnetic latitudes to high latitudes);

2) The strongest dependence of the time of the first harmonic maximum on the geomagnetic latitude is observed before a magnetic storm and after restoration of cosmic ray intensity to the normal level. In the period immediately after the main phase of the magnetic storm, the dependence on latitude is greatly weakened.

The change of the first harmonic phase with latitude for the periods before the storm and after the restoration — that is, in relatively quiet periods — may be understood if one assumes that the source of this anisotropy

is far removed from the Earth. Then the detected change of the phase may be completely explained by the influence of the geomagnetic field on the trajectories of the primary particles.

The presence of a weaker phase shift immediately after the beginning of a magnetic storm in comparison with the cases before the storm and in the period when the intensity of the cosmic rays is restored is still difficult to understand.

The laws governing the behavior of the change of the first harmonic amplitude are more complicated; very diverse cases have been observed (Table 21).

In Table 21 data are presented concerning the change of the solar-diurnal anisotropy (amplitude and phase) for 16 magnetic storms occurring in 1957-1959.

It is naturally difficult to comprehend and to give a complete interpretation of the results presented above. The question of the nature of cosmic ray anisotropy (both the first and the second harmonic) remains to a significant extent open. Only recently have we succeeded in establishing that during magnetic storms two sources of anisotropy exist. One source which is remote acts outside the influence of the geomagnetic field on the trajectories of cosmic rays. This source is most likely associated with the electric fields which arise in the observer's coordinate system during the motion of the plasma of corpsular streams having frozen-in magnetic fields. It also is associated with the asymmetric scattering of particles by magnetic fields which are frozen-in in the streams. An important role is also played by the reflection of particles from the magnetic cushion (with a small acceleration), by the drift of particles from the sun under the action of mutually perpendicular electric and magnetic fields (independently of the character of the fields in the streams, etc. (see, for example, [91, 92]). All these mechanisms exert their effect far from the earth. Evidently many

TABLE 21. PATTERNS OF CHANGE IN DIURNAL VARIATION
IN THE PERIODS OF 16 MAGNETIC STORMS

Date	Character of commencement	Character of first harmonic anisotropy		Character of second harmonic anisotropy	
		Amplitude	Phase	Amplitude	Phase
[illegible]	S	C	C	C	C
[illegible]	I	I	to Lat	I	to Lat
[illegible]	[illegible]	[illegible]	to Lat	C	to Lar
Aug 29	S	D	C	C	C
Oct 21	[illegible]	C	to Lar	C	to Lat
Nov 11 1958	--	I	C	C	to Lat
Mar 9	--	--	C	C	to Lat
Mar 26	[illegible]	I	C	C	C
Sep 3	[illegible]	C	C	C	C
Oct 22	S	I	to Lar	C	C
Dec [illegible]	[illegible]	D	to Lar	D	C
Dec 12	[illegible]	D	to Lar	D	C
Feb 11 1959	[illegible]	C	C	D	C
Mar 26	[illegible]	C	C	C	C
[illegible]	[illegible]	D	C	C	C
[illegible]	S	C	C	C	C

Key to table: C - small; M - moderate; L - large; VL - very large;
I - irregular; S - sudden;
C - changing; I - increasing; D - decreasing;
to Lat - time of maximum shifted to later hours;
to Lar - time of maximum shifted to earlier hours.

the enumerated types of disturbed diurnal variations may be understood on the basis of this theory.

Furthermore, the anisotropy of cosmic rays during magnetic storms is also caused by a close source, whose effect shows up in sphere influence of the earth's magnetic fields on the trajectories of cosmic particles. In [93] this near source was identified with the asymmetric character of the geomagnetic field change associated with the interaction of the plasma of solar corpuscular streams with the geomagnetic field.

11. Anisotropy Energy Spectrum During Magnetic Storms

For the magnetically quiet and disturbed days from October 21 through November 2, 1959 which were investigated above, the energy spectrum was calculated based on the averaged data of October 21-22 (quiet period), separately for October 27 and 28, and based on the averaged data of November 1 and 2 (after the intensity restoration) — periods I, II, IV and V respectively.

The energy spectrum for all four cases has the power-law form:

$$\frac{\delta D(\varepsilon)}{D(\varepsilon)} = \begin{cases} a\varepsilon^{-\gamma} & \text{for } \varepsilon \geqslant \varepsilon_1, \\ 0 & \text{for } \varepsilon \leqslant \varepsilon_1. \end{cases}$$

The values of a and γ, which were found from the experimental data are presented below:

	I	II	IV	V
a	0,16	0,12	0,14	0,17
γ	0,56	0,48	0,46	0,52

On the average over the four periods:

$$\frac{\delta D(\varepsilon)}{D(\varepsilon)} = 0{,}15\,\varepsilon^{-0{,}5} \text{ for } \varepsilon > \varepsilon_1 \simeq 4{,}5 - 5 \text{ BeV}.$$

From the data presented it is seen that for the relatively quiet periods I and V the spectra are slightly steeper than in the disturbed periods II and IV, although, considering the error, here one can only talk about the tendency of the spectrum to harden on magnetically disturbed days.

Let us investigate the energy spectra of the solar-diurnal variations during the magnetic storms of November 1-2, 1958, April 11-13, 1960 and April 29-30 and May 1, 1962. The study was carried out on the basis of data from the global network of stations recording the neutron component of the cosmic ray intensity which were corrected for the barometric effect. A harmonic analysis was carried out, using data corrected for the Forbush effect, by the method of double moving averages with a 24-hour period. To decrease the statistical error, an averaging of the data was carried out over latitudinal zones with mean cutoff rigidities of 1, 1.6, 2.7, 4.3, 6 and 12.8 BeV.

In Figure 63 the change in cosmic ray intensity and the H-component of the earth's magnetic field is shown for a number of stations on November 1 and 2, 1958 (LT), April 11-13, 1960, April 29-30 and May 1, 1962. From the data presented it is seen that a clearly expressed diurnal variation takes place both in the cosmic rays and in the geomagnetic field. It is /69 seen that the data of the cosmic rays have a well-expressed inverse correlation with the H-component for cases a and b when moderate magnetic storms were observed. For case c, a direct correlation occurs, when the geomagnetic field was restored after the Forbush effect. According to [94, 95], during magnetic storms which caused Forbush effects two reasons for the anisotropy of cosmic rays exist. These two reasons lead to the anomalous properties of the diurnal variation. For the cases being studied by us, when the solar-diurnal variation of the cosmic rays is in opposite phase with the diurnal variation of the H-component a local source probably appears — with an increase of the geomagnetic field, the cutoff rigidity of cosmic rays also will be increased, which leads to a decrease in cosmic ray intensity.

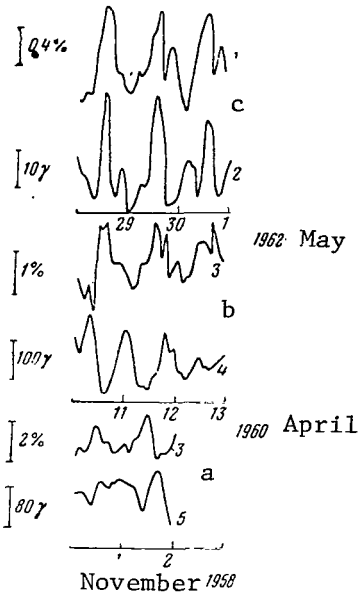


Figure 63. Change in the intensity of cosmic rays and the earth's magnetic field in the periods:

a - November 1-2, 1958; b - April 11-13, 1960; c - April 29, 30 and May 1, 1962; data from the stations: 1 - Pic-du-Midi; 2 - Ashkhabad; 3 - Norikura; 4 - San Juan; 5 - Kakioka.

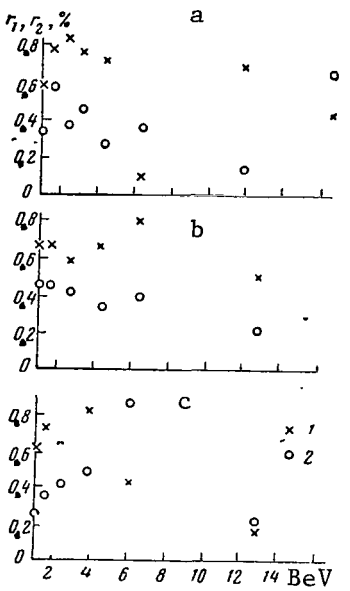


Figure 64. The amplitude of the diurnal harmonic (1) and semi-diurnal harmonic (2) as a function of the cutoff energy:

a - November 1, 1958; b - April 12, 1960; c - May 1, 1962.

In case c, when the solar-diurnal variation of cosmic rays is found to be in phase with the diurnal variation of the magnetic field, we have a disturbed solar-diurnal variation due to the action of a remote source.

In Figure 64 the amplitudes of the diurnal and semidiurnal variations are represented as a function of the cutoff energy for November 1, 1958 (a), April 12, 1960 (b) and May 1, 1962 (c). It is seen that, with an increase of the cutoff energy, the amplitude of the diurnal and semidiurnal variations decreases, that is, the spectrum of the variations $\delta D(\varepsilon)/D(\varepsilon)$ decreases with an increase in energy.

The amplitude of the semidiurnal variation on certain days closely coincides with the diurnal variation amplitude for the stations with a threshold >13 BeV (thus, for 1960 the correlation coefficient equals 0.74; for May 1, 1962 it equals 0.89). In the equatorial region the semidiurnal variation amplitude begins to increase, and becomes larger than the amplitude of the diurnal variation. A relatively high correlation between the amplitudes of the diurnal and semidiurnal variations makes it possible to assume that the /70
mechanism of their formation to a certain degree is the same.

By means of the coupling coefficients, with consideration of the latitude dependence of the diurnal variation, the energy spectrum was calculated for the periods being studied. The spectrum had a power-law form. The values the exponents are given below.

Period	γ	Period	γ
Nov. 1, 1958	0.33	Apr. 13, 1960	0.32
Nov. 2, 1958	0.36	Apr. 29, 1962	0.42
Apr. 1, 1960	0.30	Apr. 30, 1962	0.40
Apr. 12, 1960	0.34	May 1, 1962	0.45

It is seen that the spectrum when moderate magnetic storms were observed — that is, November 1-2, 1958 and April 11-13, 1960 — is harder than the spectrum for the cases of April 29-30 and May 1, 1962 when the magnetic field was still relatively quiet and the intensity of the cosmic rays still was not restored to the level preceding the Forbush effect. Naturally, in this case one can talk only about the qualitative aspect — more accurately, about the tendency toward an increase of the spectrum hardness. For a more detailed analysis, it is necessary to have data from the superinstruments.

One should note that, when calculating the energy spectrum of the diurnal variation in the case of a near source, it is incorrect to use the latitude dependence, since the anisotropy is found at a limited distance from the Earth. But by taking into account the position of the source (localized in the earth's magnetosphere) far from the earth's surface, in the first

approximation, it is entirely possible to calculate the energy spectrum taking into account the latitudinal dependence. The calculations showed that the asymptotic trajectories for the cosmic rays from the remote and near sources differ significantly only for latitudes higher than 50° [96].

The amplitude of the diurnal and semidiurnal variations was studied as a function of the geographic longitude for stations with a cutoff energy from 1 to 3 BeV for November 1, 1958. The results showed that the amplitude of the diurnal variation is largest in the western hemisphere, and toward the east it gradually decreased. This implies that the local source exerts the predominant influence on diurnal variations during magnetic storms. For the semidiurnal variation, a longitude dependence was absent.

The time of the maximum of the diurnal variation gradually was shifted to earlier hours with an increase in cutoff energy. It is impossible to say anything definite about the phase of the semidiurnal variation.

From what was presented above, one can draw the conclusion that during Forbush a Forbush effects the increased diurnal variations (ii comparison with) the quiet period) have a different origin (near and remote sources).

The energy spectra are accordingly different. The near source produces a spectrum which is slightly harder; the far source produces a softer one.

It is of interest to investigate the behavior of the solar-diurnal and semidiurnal variations in the intensity of cosmic rays during disturbed periods in the phase of decreased solar activity. For this purpose, based on the data of the global network of stations recording the neutron component of the cosmic rays, an analysis was made of the solar-diurnal and semidiurnal variations for a number of magnetically disturbed periods occurring in 1963. Days were included here when the disturbance was observed only in the form of increased diurnal variations in the intensity of the cosmic rays. The earth's magnetic field at this time was relatively quiet.

TABLE 22. MEAN CUTOFF RIGIDITIES FOR THE LATITUDE ZONES I-VI (in BeV)

Periods	I	II	III	IV	V	VI
a	0,50	1,90	2,66	4,30	5,55	10,70
b	0,50	1,57	2,14	3,52	5,47	14,18
c	0,31	0,99	1,73	2,66	5,67	12,83
d	0,19	0,13	1,90	2,66	5,67	12,44

When studying the energy characteristics of the solar-diurnal anisotropy and investigating the change in time of maximum at various latitudes, an analysis was made in all cases for separate days. To increase the precision, the data were averaged in local time for each day over the number of stations which were separated beforehand into six latitudinal zones. The aperiodic and periodic variations with a period larger than a day were eliminated by the moving averages method. /71

The solar-diurnal anisotropy for each day was investigated in the periods from January 25 through 31, 1963 (a); from April 26 through May 20, 1963 (b); from May 25 through July 13, 1963 (c); from September 10 through October 10, 1963 (d).

The average cutoff rigidity for the zones for each of the four periods listed is presented in Table 22. /72

The studies showed that both the solar-diurnal and semidiurnal variations varied in rather broad limits from day to day both in amplitude and also in phase. Accordingly, in the region of high latitudes on certain days the amplitude of the solar-diurnal variation had the least value ($\sim$0.1-0.2%). On other days, on the other hand, at high latitudes the amplitude was at a maximum. For example, in Figure 65 the amplitudes of the first and second harmonics are presented as a function of the cutoff rigidity. One may note that on certain days the change in second harmonic amplitude has

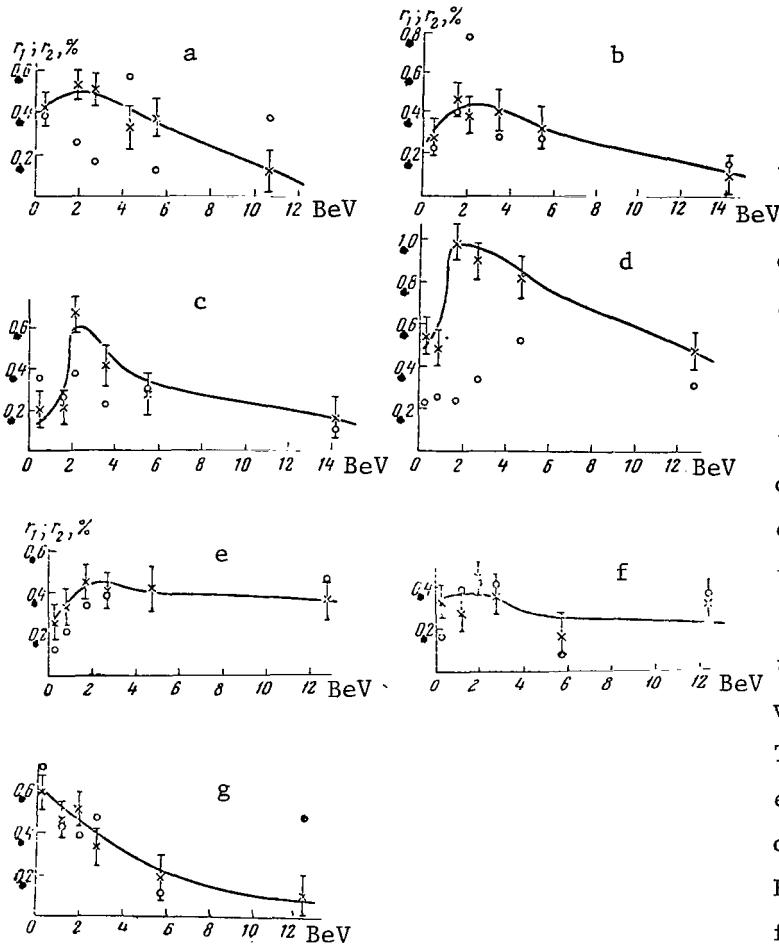


Figure 65. The first harmonic (small crosses) and second harmonic (small circles) as a function of cutoff rigidity for 1963.

a - January 30; b - May 15; c - May 19; d - July 3; e - July 10; f - September 10; g - September 20.

a high positive correlation with the first harmonic amplitude. This fact to some extent may indicate, as we already mentioned above, hat the diurnal and semi-diurnal variations have the same nature.

Using the dependence of the amplitude of the solar-diurnal variation on the cut-off energy[1] and using the coupling coefficients [2] the energy spectra of the solar-diurnal anisotropy were calculated for each day. The calculations of the energy spectra for a number of days are presented in Figure 66 (days were taken for which the behavior of the amplitude as a function of the cutoff energy was shown in Figure 65).

In all the cases investigated by us, it is possible to describe the energy spectrum by a power-law function of the form $\frac{\delta D(\varepsilon)}{D(\varepsilon)} = a\varepsilon^{-\gamma}$ where the exponent for various days changes within broad limits. In Table 23 values are presented of the exponent γ of the anisotropy energy spectrum.

[1] The values of the rigidity thresholds were taken from Reference [65].

TABLE 23. VALUES OF THE EXPONENT γ OF THE ANISOTROPY ENERGY SPECTRUM FOR 1963

Date	γ	Date	γ	Date	γ	Date	γ
Jan.30	0.85	May 6	0.23	June 28	0.97	Sept.20	0.17
Apr.30	0.87	May 15	0.03	July 3	0.58	Sept.21	0.81
May 3	0.21	May 18	0.10	July 10	0.21	Sept.26	0.35
May 4	0.12	May 19	0.20	Sept. 10	0.30	Sept.28	0.22
May 5	0.19	June 25	0.44	Sept. 17	0.71	Oct. 10	0.46

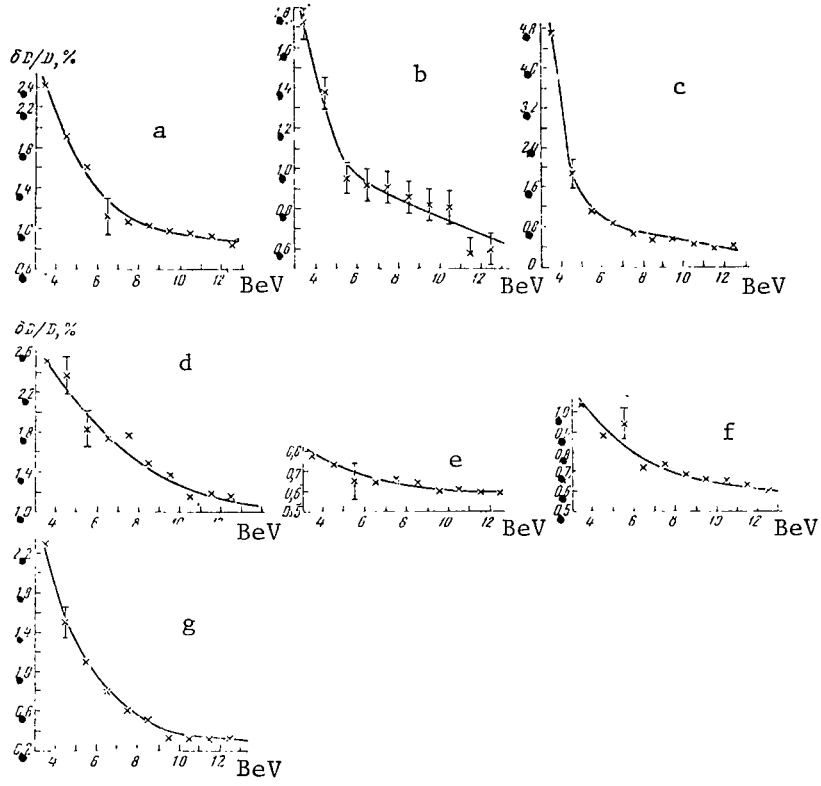


Figure 66. The energy spectrum of the diurnal anisotropy for separate days.

The designations are the same as in Figure 65.

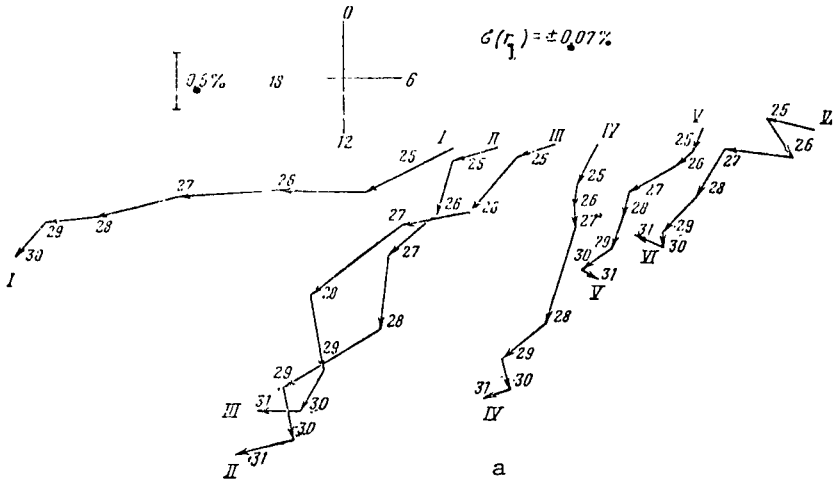
The table shows that γ varies from 0 to 0.9. As was mentioned above, on specific days in the region of low energies the amplitude of the solar-diurnal variations has a high value and sharply decreases with an energy /73 increase. This may be explained by the fact that on specific days favorable conditions are observed when particles of low energies participate in the formation of the solar-diurnal variation, that is the lower boundary of the spectrum is shifted to the region of lesser energies.

It is also necessary to mention that during quiet periods and in certain other cases [52, 65] the amplitude of the semidiurnal variations increases at stations with a cutoff energy of 12-15 BeV.

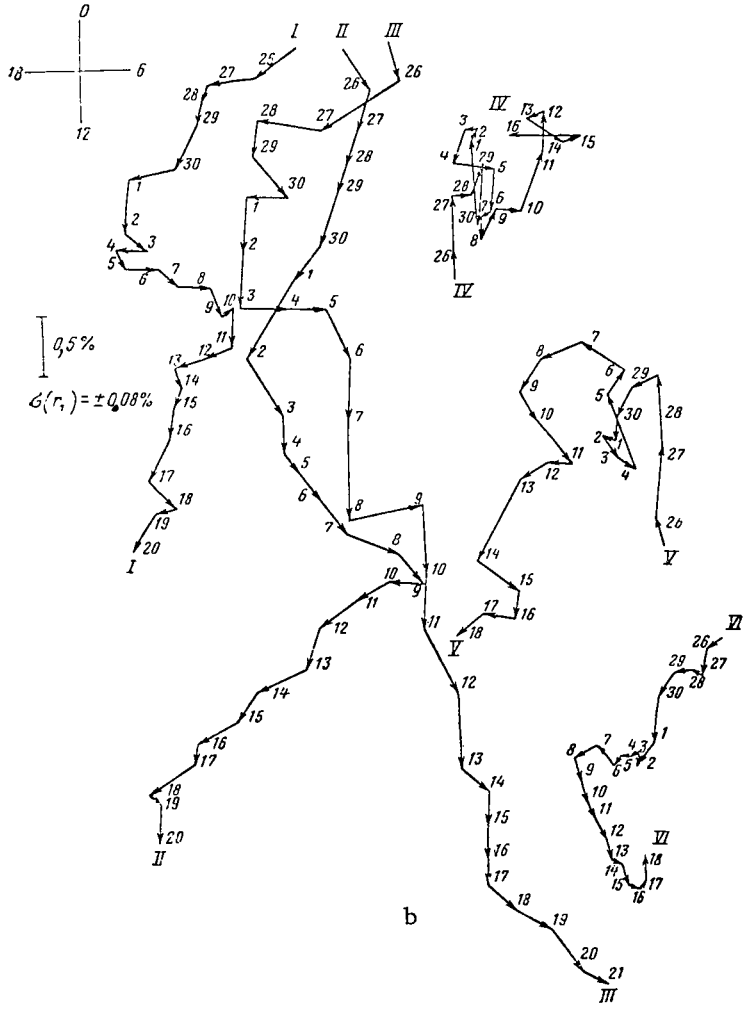
To analyze the phase of the solar-diurnal variation on separate days, especially its changes over days at various latitudes, we constructed harmonic diagrams for each zone. These diagrams are presented in Figure 67, a-d. From the figures presented it is seen that the phase changes of the solar-diurnal variations in various latitude zones are different. The time of the maximum at the middle latitudes is earlier (even relative to the equatorial stations). Thus, in Figure 67,a, one may distinguish zone IV; in Figure 67,b — zone II; in Figure 67,c — zones III and V; in figure 67,d — zone IV. In the zones distinguished, the time of the maximum is least relative to the other zones. In the quiet periods, the time of the maximum is shifted with a latitude decrease to earlier hours in accordance with the function $t_{max} = b - a \cos \lambda$, where λ is the geographic latitude [65, 97].

The anomalous shift of the time of the maximum to earlier hours in the middle latitudes probably can be explained by the influence on the phase of the asymmetric change of the rigidity threshold during magnetically disturbed periods. This becomes clear if one considers that the most sensitive region of the rigidity threshold change is found in the middle latitudes.

Thus, summarizing the cited data on the energy characteristics of the anisotropy during magnetic storms and Forbush effects, one can note that the



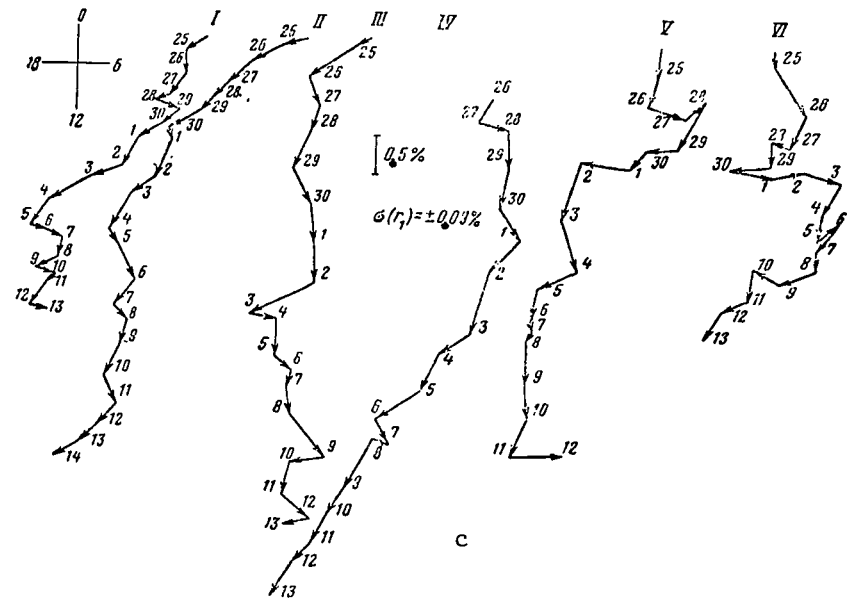
a



b

Figure 67. Harmonic diagrams of the first harmonics during disturbed periods in 1963.

a - January (the numbers on the vectors are the dates);
b - April-May;



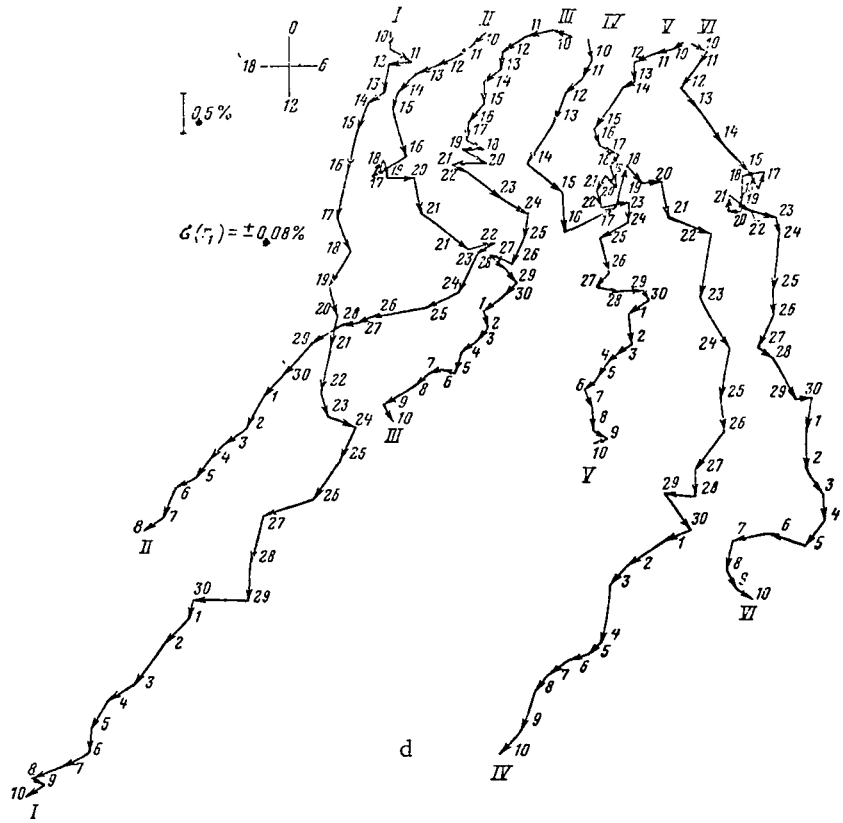


Figure 67. (cont'd) c - June-July; d - September-October; I-VI - latitude zones, the cutoff rigidities for which are presented in Table 22 on p. 72*.

*Translator's Note: This corresponds to English page 108.

anisotropy energy spectrum during magnetically disturbed periods in some cases becomes harder and in other cases, on the other hand, is softened.

12. Semidiurnal Variation of Cosmic Rays

1) The Amplitude of the Semidiurnal Anisotropy of Cosmic Rays as a Function of Cutoff Energy and Solar and Geomagnetic Activity

To clarify the nature of semidiurnal anisotropy, it is important to know the correlation of the amplitude and phase of this anisotropy with solar (sunspot number) and geomagnetic (K_p index) activity. In Figure 68 the amplitude of the semidiurnal variation is presented as a function of the cutoff energy. It is seen that the amplitude of the semidiurnal variations in the region of high latitudes has a certain tendency to increase (0.10 - 0.15%). It then remains almost constant, and in the region of low latitudes it increases up to 0.3%. Thus, there is a definite dependence of the semidiurnal variation on the cutoff energy. /76

The changes in time of the amplitude of the semidiurnal variations, of sunspot number W, and the K_p index are presented in Figure 69. The mean monthly values of the K_p indexes (small crosses), the sunspot number W (small triangles) and the amplitudes of the semidiurnal anisotropy (dots) are presented separately for each latitudinal zone. The amplitude change of the second harmonic in all zones except for the low-latitudinal zones (a cutoff rigidity of 14.1 and 16.2 BeV) has a global character. It has no definite relationship with solar or geomagnetic activity. In Table 24 the numerical values of the correlation coefficients between the amplitude of the second harmonic, sunspot number and K_p index are given as calculated on the basis of mean monthly data of 1958.

Let us investigate the results of the analysis for the period close to the solar activity minimum (1962). In Figure 70 the mean monthly values of

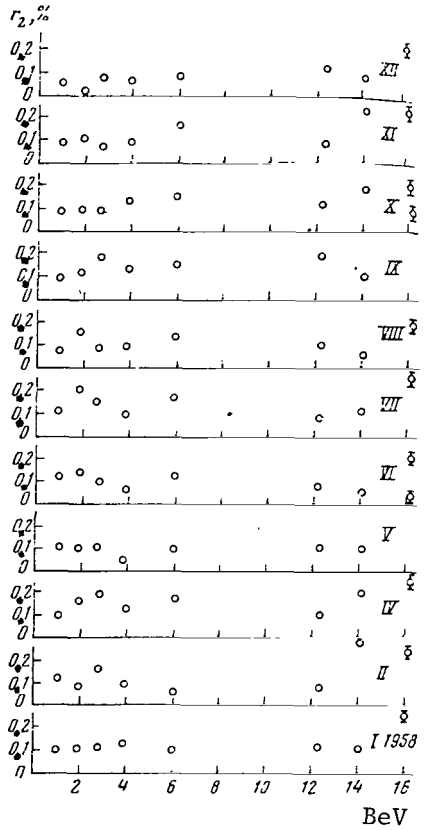


Figure 68. Amplitude of the semi-diurnal variation as a function of the cutoff energy based on neutron component data during the periods I, II, IV-XII, 1958.

TABLE 24. CORRELATION COEFFICIENTS BETWEEN THE AMPLITUDE OF THE SECOND HARMONIC AND THE CHARACTERISTICS OF SOLAR AND MAGNETIC ACTIVITY BASED ON THE DATA OF 1958

Latitude belt with mean cut-off energies in BeV	Correlation coefficients between:	
	Amplitude of the second harmonic and sunspot number	Amplitude of the second harmonic and the K_p index
1,00	0,22	0,37
1,88	0,21	0,35
2,74	0,27	0,11
3,88	0,21	—0,23
6,40	0,24	—0,10
12,30	0,69	—0,50
14,10	0,73	—0,09
16,20	0,33	0,06

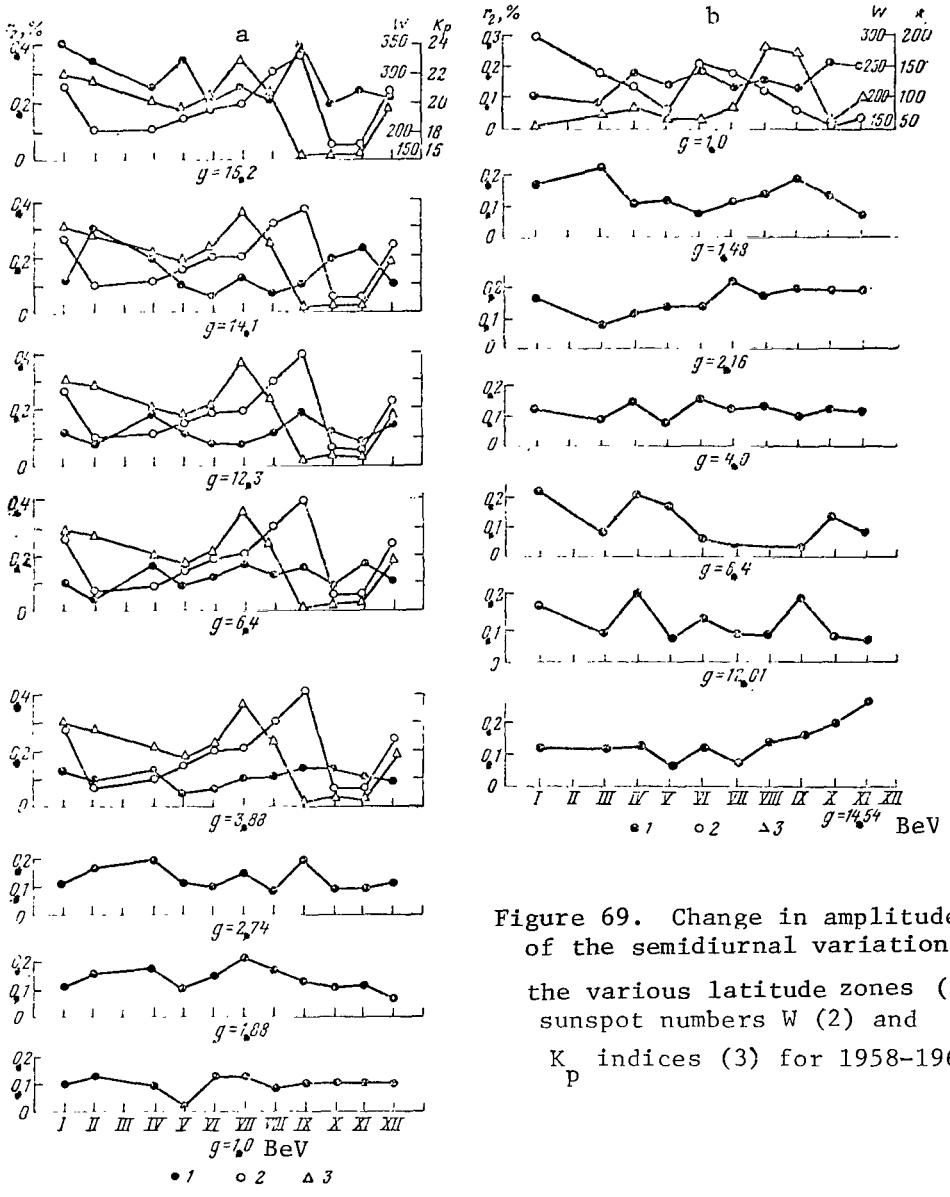


Figure 69. Change in amplitude of the semidiurnal variation r_2 for the various latitude zones (1), sunspot numbers W (2) and K_p indices (3) for 1958-1961 (a-d).

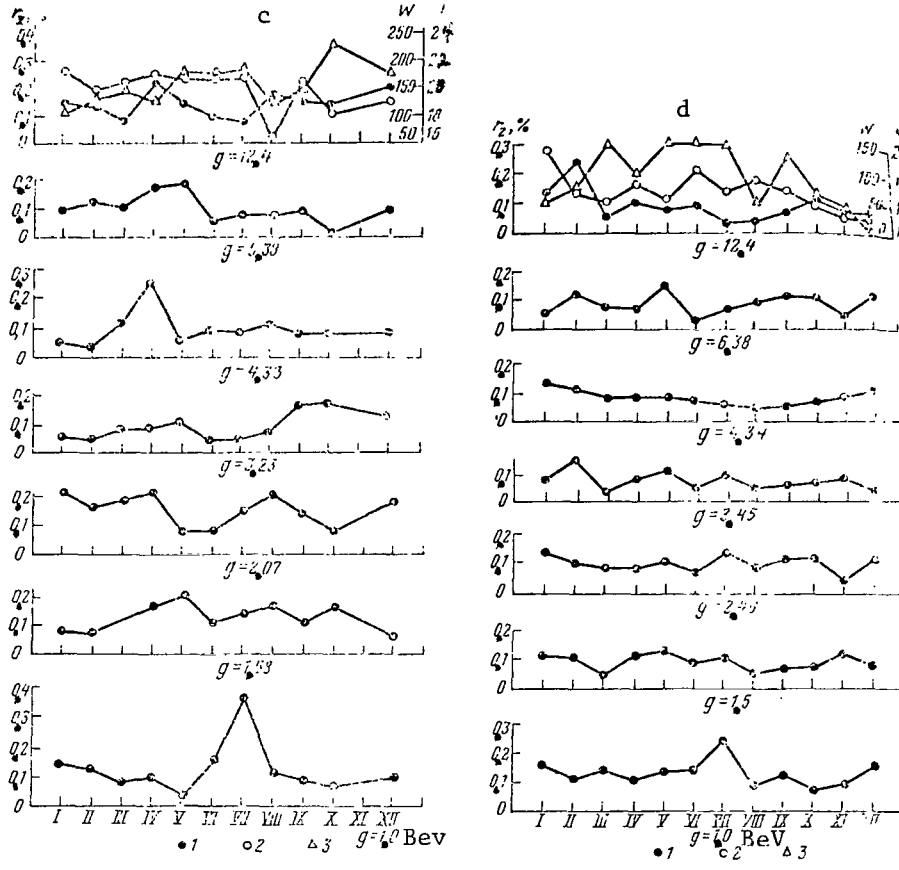


Figure 69. (cont'd)

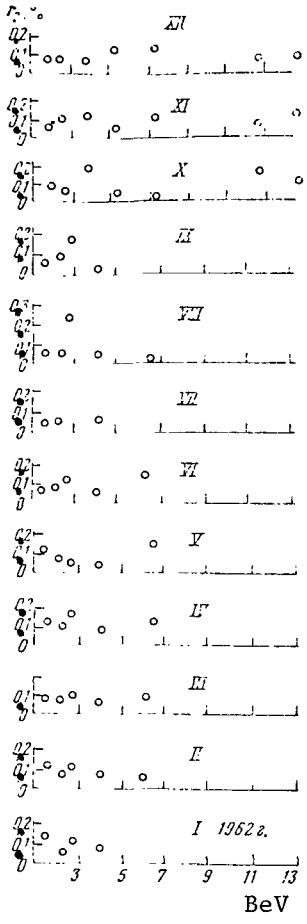


Figure 70. Amplitude of the semidiurnal variations as a function of the cutoff energy g (in BeV) in 1962.

the amplitude of the semidiurnal variations are presented as a function of the cutoff energy. As is seen from the figure, no definite relationship with cutoff rigidity is observed within the limits of errors. /77

The data on the amplitude of the second harmonic, sunspot number, and K_p index for 1962 are shown separately for each belt in Figure 71. The correlation coefficients between the amplitude of the semidiurnal variations, sunspot number, and K_p index are presented in Table 25. No definite correlation is observed in the data, although one may notice that the correlation coefficient between the amplitude of the semidiurnal variations and the sunspot number is larger than between r_2 and the K_p index. This fact indicates that basically a remote source is responsible for the semidiurnal variation in quiet periods.

In Figure 72 the mean annual values of the semidiurnal variation amplitudes are presented as a function of the mean cutoff energy. It is seen that there is no definite dependence of the change in time of the semidiurnal variation on the cutoff energy. /78

In Figure 73 the amplitude of the semidiurnal variation is shown separately as a function of time for each zone. One may conclude that a reduction

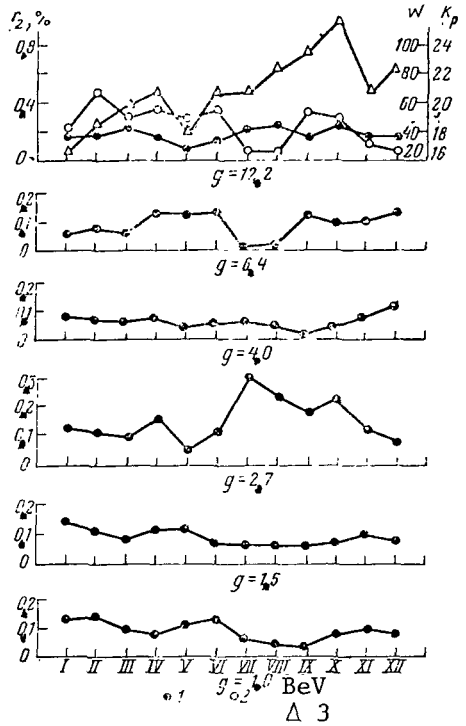


Figure 71. Values of the amplitude of the second harmonic for the various latitude zones (1), sunspot numbers W (2) and K_p indices (3) May 1962.

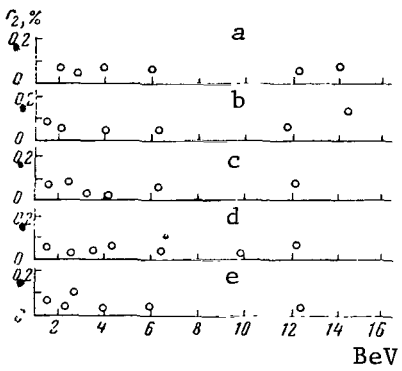


Figure 72. Mean annual values of the amplitude of the semidiurnal variation as a function of cutoff energy 1958-1962. (a-e).

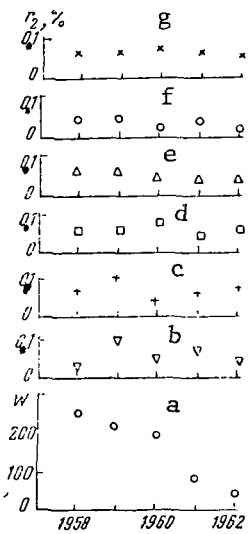


Figure 73. Change in sunspot number W and the amplitude of the semidiurnal variations during the course of 1958-1962 in the latitude zones:

a - the number of sunspots; b - the mean cutoff energy of 1.0 BeV; c - 1.5 BeV; d - 2.5 BeV; e - 4.0 BeV; f - 6.0 BeV; g - 13.0 BeV.

TABLE 25. CORRELATION COEFFICIENTS BETWEEN THE AMPLITUDE OF THE SECOND HARMONIC AND THE CHARACTERISTICS OF SOLAR AND MAGNETIC ACTIVITY BASED ON THE DATA OF 1962

Latitude zone with mean cut-off energies in BeV	Correlation coefficients between: Amplitude of the second harmonic and sunspot number	Amplitude of the second harmonic and the K_p index
1,0	0,52	—0,12
1,5	0,49	—0,30
2,7	—0,55	0,39
4,0	0,14	0,14
6,4	0,77	0,33
12,2	—0,57	0,14

of the semidiurnal variation amplitude takes place with the transition from the maximum to the minimum of solar activity (this is especially clearly seen from the data for middle-latitude stations).

In Figure 74 the mean monthly amplitudes of the second harmonic are presented as a function of the first harmonic. The figure shows that in general no definite correlation between the amplitudes of the first and second harmonics is observed for the high- and middle-latitude zones. Only for the low-latitude zones (12.4 BeV — Figure 74, a; 12.4 BeV — Figure 74, b; 12.2 BeV — Figure 74, c), in the period 1958-1960, is there a noticeable increase in the amplitude of the second harmonic with an increase in the first harmonic amplitude. This indicates that at the equatorial stations the diurnal and semidiurnal variations have the same nature. This is most distinct in years of a solar activity maximum. The same is also seen from Table 26 where the correlation coefficients between

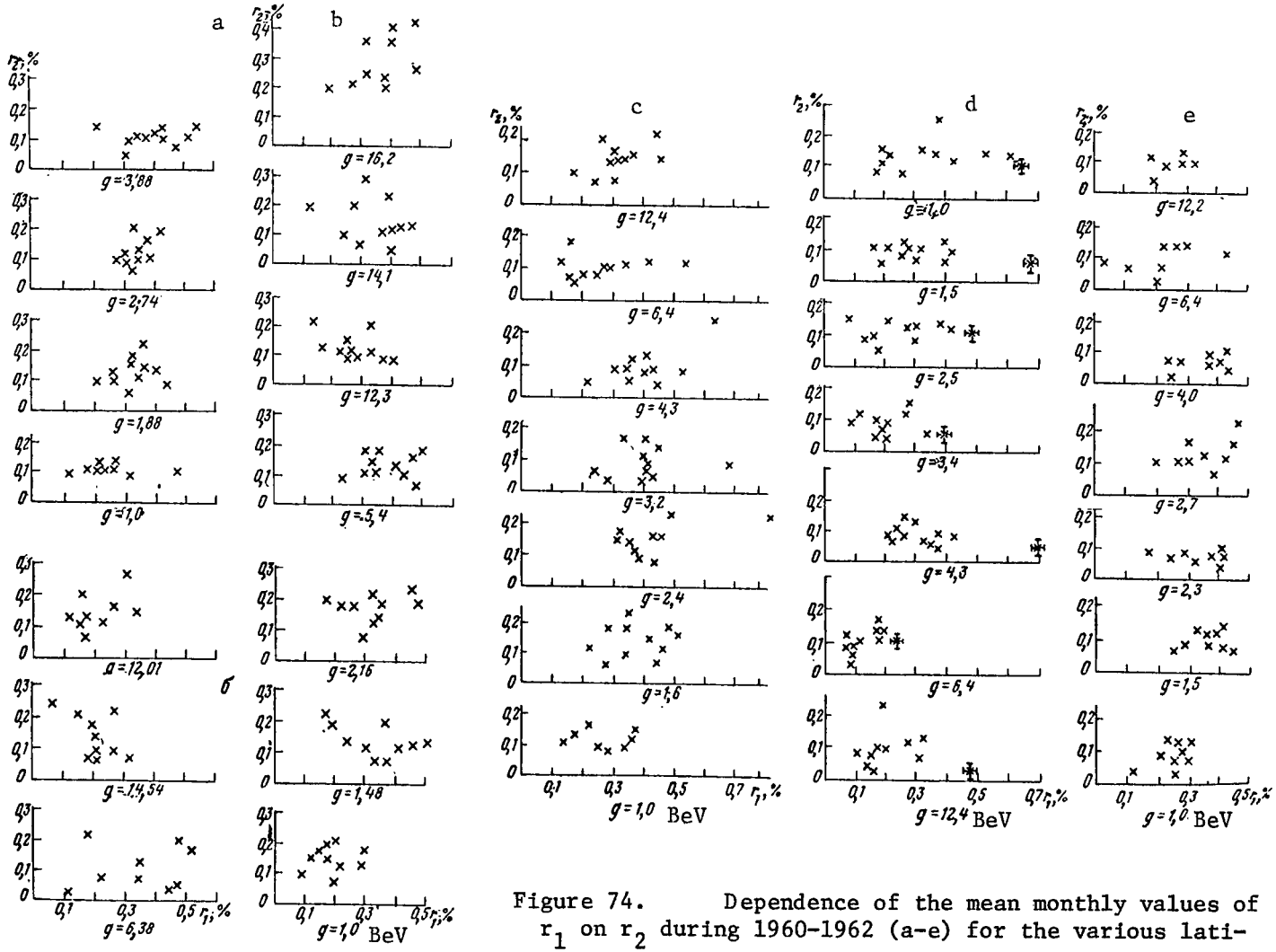


Figure 74. Dependence of the mean monthly values of r_1 on r_2 during 1960-1962 (a-e) for the various latitude zones.

*Translator's note: Commas represent decimal points.

TABLE 26. CORRELATION COEFFICIENTS BETWEEN THE AMPLITUDES OF THE FIRST AND SECOND HARMONICS

1958		1959		1960		1961		1962	
g in BeV	r_1 r_2	g in BeV	r_1 r_2	g in BeV	r_1 r_2	g in BeV	r_1 r_2	g in BeV	r_1 r_2
1,00	0,12	1,0	0,23	1,0	0,20	1,0	—0,10	1,0	0,45
1,56	0,22	1,5	0,22	1,6	0,16	1,5	—0,32	1,5	0,12
2,74	0,58	2,2	0,20	2,4	0,30	2,5	—0,06	2,3	0,12
3,88	0,05	4,0	—0,29	3,2	0,13	3,4	—0,14	2,7	0,11
6,00	0,08	6,40	0,14	4,3	0,33	4,3	—0,37	4,0	0,26
12,30	—0,21	12,1	0,05	6,4	0,21	6,4	—0,36	6,4	0,47
14,07	—0,17	14,5	0,61	12,4	0,50	12,4	—0,11	12,2	0,23
16,2	0,69								

the amplitudes of the first and second harmonics are presented for the period 1958-1962 for the various latitude zones.

2) Phase of the Semidiurnal Variation and its Change in Time

In 1958 the phase of the second harmonic, as is seen from Figure 75, varied in broad limits (from 0 to 12 hours), and there was no definite relationship with the cutoff energy. One can only remark that for the majority of months (8 of 11) the phase of the second harmonic in the equatorial belts (high cutoff energies) was shifted to an earlier time and was between 0.5-1.8 hours. /79

For the period 1959-1962, a similar picture was observed — the phase of the semidiurnal variation changed within broad limits and had a tendency to shift to earlier hours in the equatorial region for the majority of months.

In Figure 76 the phase of the second harmonic is presented as a function of geomagnetic latitude based on the mean annual values for 1958-1962. No definite shift of the phase with time is observed at the various latitudes, as is seen from Figure 76. In Figure 77 the mean annual values of the change in the semidiurnal variation phase are presented from year to year. It is seen that no definite correlation is observed.

Let us investigate the relation between the phases of the diurnal and semidiurnal variations. In Table 27 the correlation coefficients between the mean monthly values of the second harmonic and the phase of the mean monthly values of the first harmonic are presented for each zone separately in 1958-1962. Table 27 shows that at the middle-latitude stations ($g = 2.74$-3.88 BeV) — when the phase of the first harmonic shifts to later hours — the phase of the second harmonic changes clockwise, that is, it is displaced on the average from 10 to 12 hours, from 12 to 10 hours, etc. At the high-latitude stations (cutoff energy of 1-2 BeV) no such relationship is observed. In the middle-latitude zone of 2.6 BeV, a negative

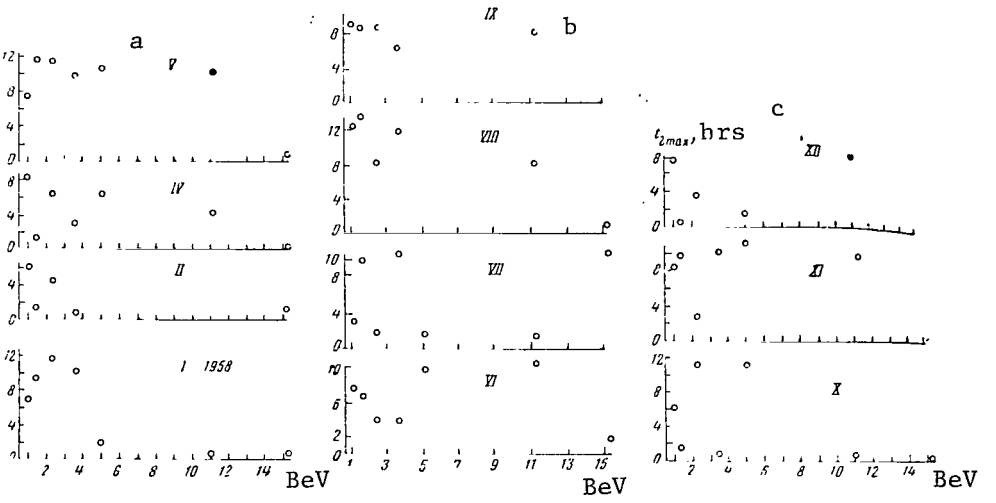


Figure 75. The Change in phase of the semidiurnal variation. in I, II, IV and V (a); VI, VII, VIII and IX (b); X, XI, and XII for 1958 (c) as a function of the cutoff energy (g) (in BeV).

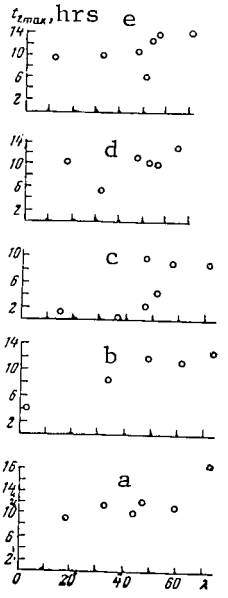


Figure 76. Phase of the second harmonic as a function of geomagnetic latitude for 1958-1962 (a-e).

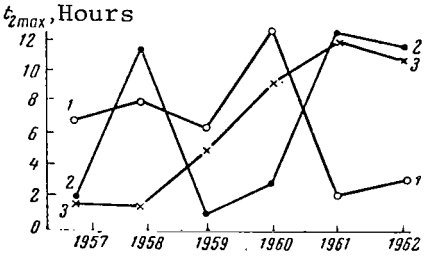


Figure 77. Change in mean annual values of the phase of the semidiurnal variation for latitude zones with a mean cutoff energy of:

1 - 1 BeV; 2 - 4 BeV; 3 - 13 BeV.

correlation is recorded; in the low-latitude zones 14.54-12.1 BeV, on the other hand, a positive correlation is observed between the phases of the first and second harmonics.

Thus in 1958 and 1959 in the region of maximum sensitive of the rigidity threshold, when the time of the maximum of the first harmonic shifts to later hours the time of the maximum of the second harmonic is shifted to earlier hours. Figure 10 (see page 28) shows that at the middle-latitude stations (cutoff energy of 2-3 BeV) with an increase of the phase of the first harmonic, /82 the phase of the second harmonic also increases.

From Table 27 one may conclude that at the middle-latitude stations (cutoff energy of 203 BeV) there is significant correlation between the phases of the diurnal and semidiurnal variations; in 1958-1959 it is negative (that is, when the time of the maximum of the first harmonic shifts to later hours, the time of the second harmonic maximum is shifted to earlier hours) and in 1960-1962 there is a positive correlation (that is, when the phase of the first harmonic shifts to later hours, the phase of the second harmonic also is shifted to later hours). /83

3) Longitude Dependence of the Amplitude and Phase of the Semidiurnal Variation

For the purpose of studying the longitude dependence of the semidiurnal variation, Figure 78 presents the mean annual amplitudes of the semidiurnal variation for the middle-latitude stations which have a cutoff energy of 1.5 - 2 2 BeV as a function of geographic longitude. The choice of this latitude zone is explained by the large number of stations it includes on the American and European continents. In this way, we eliminated the latitude /84 effect of semidiurnal variations. From Figure 78 it is seen that the amplitude of the semidiurnal variation is practically independent of geographic longitude.

In Figure 79 the phases of the mean annual vectors of the semidiurnal variation of the middle-latitudinal stations are shown as a function of

TABLE 27. CORRELATION COEFFICIENT BETWEEN THE TIME OF THE MAXIMUM OF THE FIRST HARMONIC ($t_{1\ max}$) AND THE SECOND HARMONIC ($t_{2\ max}$)

1958		1959		1960		1961		1962	
g, BeV	$t_{1\ max}$, $t_{2\ max}$	g, BeV	$t_{1\ max}$, $t_{2\ max}$	g, BeV	$t_{1\ max}$, $t_{2\ max}$	g, BeV	$t_{1\ max}$, $t_{2\ max}$	g, BeV	$t_{1\ max}$, $t_{2\ max}$
1,00	—0,28	1,0	—0,04	1,0	0,07	1,0	0,05	1,0	—0,27
1,88	0,17	1,5	0,19	1,6	0,29	1,5	—0,12	1,5	0,18
2,74	—0,58	2,2	—0,32	2,4	0,60	2,5	0,52	2,3	—0,03
3,88	—0,32	4,0	—0,20	3,2	0,51	3,4	0,35	2,7	0,39
6,00	—0,14	6,4	—0,19	4,3	0,14	4,3	0,70	4,0	0,56
12,30	0,07	12,1	0,53	6,4	0,13	6,4	—0,26	6,4	0,19
15,60	—0,13	14,5	0,37	12,1	0,21	12,4	—0,42	12,2	—0,57

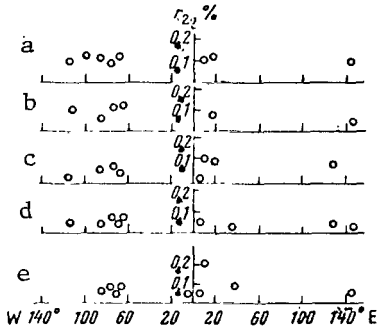


Figure 78. Amplitude of the semi-diurnal variation as a function of geographic longitude for stations with a cutoff energy of 1.5-2.2 BeV in 1958-1962 (a-e).

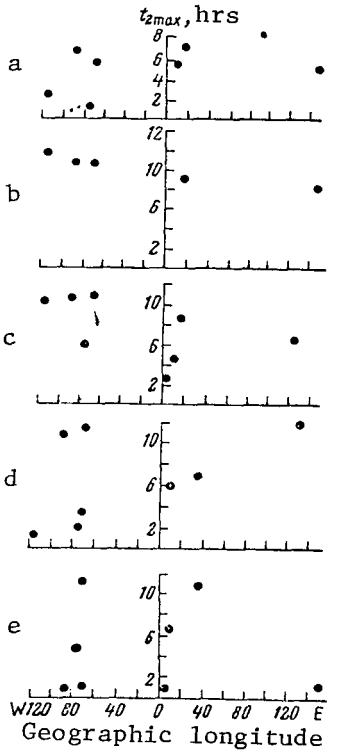


Figure 79. Phase of the semi-diurnal variation at middle latitude stations as a function of geographic longitude for stations in 1958-1962 (a-e).

geographic longitude for the various periods being studied: the phase of the semidiurnal variation does not depend on geographic longitude.

Thus, one may conclude that for the quiet periods of the various solar activity cycles the amplitude and phase of the mean annual semidiurnal variations do not depend on geographic longitude. From this, it follows that a change in the earth's magnetosphere cannot possibly be the reason for the quiet semidiurnal variations.

4) Seasonal Change in Semidiurnal Variation

In Figure 80 the deviations of the semidiurnal variation amplitude are presented as a function of the mean annual values. It is seen that a significant seasonal change in semidiurnal variation was observed in 1958 in the equatorial and middle-latitude zones with two maxima, but in 1959 a seasonal change was observed only in the equatorial zone. In 1960 a seasonal change in semidiurnal variation with a period of half a year was recorded at all stations; the maximum values occurred in the winter and summer. In 1961 a slow change in semidiurnal variation took place at all latitudes with a maximum in July-September. In 1962 two maxima were recorded during a seasonal change at the high latitudes — a spring and a fall maximum — and at the equatorial stations two maxima were recorded in the summer and in the winter. At the middle latitude stations, a gradual increase was observed from the beginning to the end of the year, with a maximum value in November.

A harmonic analysis, the data from which are presented in Table 28, showed that the first (annual) harmonic of the semidiurnal variation at the high and middle latitudes increased with a decrease in solar activity, /85 but at the equatorial stations it remained constant. The amplitude of the second harmonic at the high-latitude stations was absent, except for 1962. In 1961 it was absent at all latitudes.

An analysis of the seasonal change in semidiurnal variation also shows that current ideas concerning the nature of the seasonal change in the

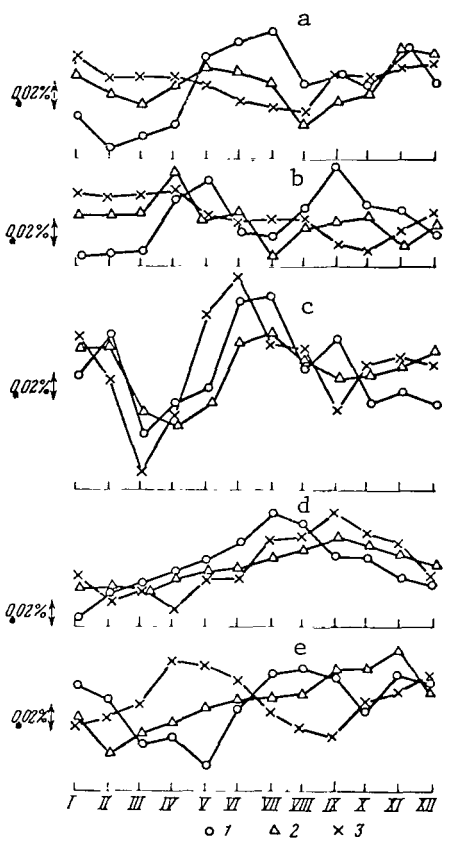


Figure 80. Seasonal change in semidiurnal variation in 1958-1962 (a-e)

1 - low latitudes; 2-middle latitudes; 3 - high latitudes.

semidiurnal variation are not able to fully explain the experimental results, and the semidiurnal variation at the Equator is not entirely explained. It is possible that the seasonal change in solar-diurnal and semidiurnal variations is caused not only by the misalignment of the magnetic dipole axis with the axis of the earth rotation, but also by another mechanism.

5) Study of Semidiurnal Variations by Means of Numerical Filters

To clarify the semidiurnal variations, the authors of [98], used a numerical filter instead of ordinary harmonic analysis. The proposed method is more effective, since it reveals the semidiurnal variations against the background of statistical variances. It consists of the following. Assuming that the data are continuous over a long time, one may write the results of the changes as a function of time in the form

$$f(t) = A(t)\cos[\omega_0 t + \Phi(t)] + N(t), \qquad \text{(II.1)}$$

where the first term represents the signal and N(t) are all the other non-periodic variations (in this case, appearing as noise). We must clarify the information which is included in the functions A(t) and $\Phi(t)$. Let us assume that the integral transforms for f(t) are given in the form

TABLE 28. SEASONAL CHANGES IN SEMIDIURNAL VARIATION

Years	Mean value of energy, r_2^2 V	Mean annual value of the amplitude of semidiurnal variation, %	First and second harmonics of seasonal change in semidiurnal variation			
			r_1^2 in % of r_2	r_2^2 in % of r_2	t_1^2 Month & day	t_2^2 Month & day
1958	1.5	0.122	12.0	4.1	Oct.16	May 7 & Nov 7
	4.2	0.137	5.0	22.2	Sep 3	June3 & Dec 3
	12.0	0.139	15.5	17.3	May 28	Jun13 & Dec13
1959	1.5	0.167	16.8	5.5	Dec 27	Mar18 & Sep18
	4.2	0.136	12.7	22.4	Jan 28	Jan27 & Jul27
	12.0	0.151	14.0	17.4	May 2	Feb20 & Aug20
1960	1.5	0.148	13.9	6.7	Nov 9	Feb21 & Aug21
	4.2	0.100	9.4	22.8	Nov 27	Feb26 & Aug26
	12.0	0.092	23.4	37.0	May 5	Mar 6 & Sep 6
1961	1.5	0.128	24.4	4.6	Aug 6	Feb 1 & Aug 1
	4.2	0.084	19.1	6.9	June25	Mar 1 & Sep 1
	12.0	0.092	26.1	6.1	May 15	May15 & Nov15
1962	1.5	0.134	51.6	27.2	Mar 20	May 7 & Nov 7
	4.2	0.066	14.6	11.6	June26	May 9 & Nov 9
	12.0	0.071	27.5	30.6	Aug 28	Mar18 & Sep18

$$C(t, \omega_0) = \int_{-\infty}^{\infty} D(t' - t) f(t') e^{i\omega_0 t'} dt', \tag{II.2}$$

where D(t)' is a function satisfying the condition

$$\int_{-\infty}^{\infty} D(t)\, dt = 1. \tag{II.3}$$

The integral Fourier transform for D(t) is

$$y(\omega) = \int_{-\infty}^{\infty} D(t) e^{-i\omega t} dt. \tag{II.4}$$

If D(t) is selected so that $y(\omega) \neq 0$ only in a small region in the vicinity of a zero frequency, then only the components of D(t) which make a contribution to $C(t, \omega_0)$ will lie in the band around ω_0. In this case /86

$$\begin{aligned} C(t, \omega_0) &= \overline{A(t)\cos[\omega_0 t + \Phi(t)]\cos(\omega_0 t)} + \\ &+ i\overline{A(t)\cos[\omega_0 t + \Phi(t)]\sin(\omega_0 t)} + C_N = \\ &= \frac{1}{2}\overline{A(t)\cos[\Phi(t)]} + \frac{1}{2}\overline{A(t)\cos[2\omega_0 t + \Phi(t)]} + \\ &+ \frac{i}{2}\overline{A(t)\sin[-\Phi(t)]} + \frac{i}{2}\overline{A(t)\sin[2\omega_0 t + \Phi(t)]} + C_N. \end{aligned} \tag{II.5}$$

If N(t) is the noise, the energy of which per unit frequency interval in the vicinity of ω_0 is small in comparison with the energy $A(t)\cos[\omega_0 t + \Phi(t)]$ in this same region, then in the first approximation one is able to disregard C_N. This gives

$$C(t, \omega_0) = \frac{1}{2} A(t)\cos[\Phi(t)] - \frac{i}{2} A(t)\sin[\Phi(t)] = \frac{A(t)}{2} e^{-i\Phi(t)}, \tag{II.6}$$

finally we have:

$$\begin{aligned} A(t) &= 2\,|C(t, \omega_0)|, \\ \Phi(t) &= -\arg C(t, \omega_0). \end{aligned} \tag{II.7}$$

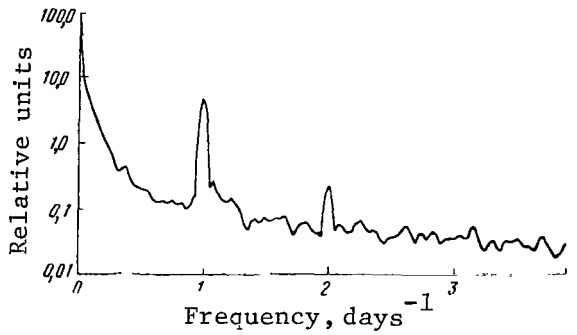


Figure 81. The spectrum of the distribution of frequencies for the neutron monitor at Deep River during 1964.

Above to the right is shown the 60-percent confidence interval.

In Figure 81 a typical spectrum is shown for the neutron monitor at Deep River. A substantial peak is observed in the spectrum in two cycles of the day which indicates the presence of a semidiurnal variation. In con- Accordingly, the amplitude emerges. quite clearly beyond the limits of the noise in the vicinity of this peak. The relatively narrow peak ($\sim$0.1) obtained points to the advantage of using a narrow-band filter.

For these same purposes, one generally is able to express the signal function f(t) by a Fourier series in a certain finite interval with an extent T centered at t_0. This gives /87

$$f(t) = \sum_{-\infty}^{\infty} C_n(t_0, \omega_n)\, e^{i\omega_n t}, \quad t_0 - \frac{T}{2} \leqslant t \leqslant t_0 + \frac{T}{2}, \tag{II.8}$$

$$C_n(t_0, \omega_n) = \frac{1}{T} \int_{t_0 - \frac{T}{2}}^{t + \frac{1T}{2}} f(t)\, e^{-\omega_n t}\, dt. \tag{II.9}$$

The corresponding expression for D (t) is

$$D_0(t) = \begin{cases} \frac{1}{T}, & t_0 - \frac{T}{2} \leqslant t \leqslant t_0 \pm \frac{T}{2}, \\ 0 \text{ outside this region} \end{cases} \tag{II.10}$$

This shows that classical harmonic analysis is a particular case of the more general process described in (II.2). Such processes may be called complex demodulation, since they correspond to the inverse of the process of complex modulation — that is, to the simultaneous modulation of amplitude and phase.

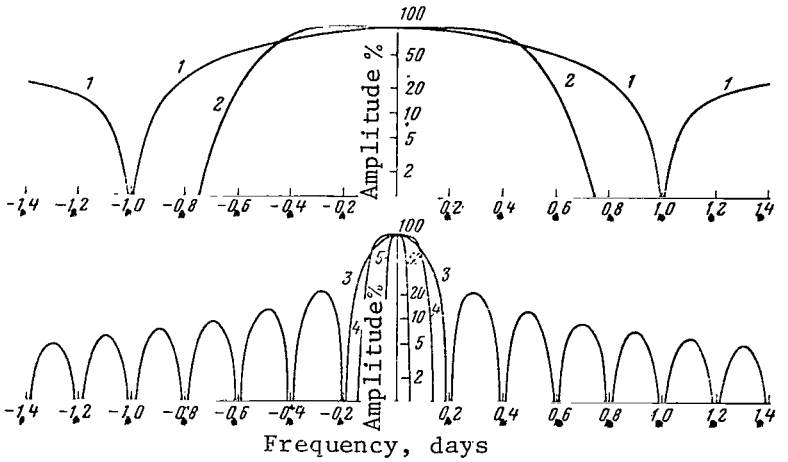


Figure 82. Results of calculations for the selection of the most effective filter:

1 - diurnal harmonic analysis; 2 - filter No. 1 (a day was taken during the ascent); 3 - five-day moving averages of the diurnal harmonic analysis; 4 - filter No. 2 (5-day ascent time); 5 - filter No. 3 (15-day ascent time).

Three filters were used in the form

$$D(t) = Ne^{-\beta t^2}\frac{\sin \alpha t}{t}, \qquad \text{(II.11)}$$

where α defines the width of the filter band; N is a constant, satisfying the condition (II.3). A fourth filter of the form (II.10) was used for ordinary harmonic analysis for purposes of comparison.

Considering the value of $D_0(t)$, in accordance with (II.10), we are able to write

$$|y_0(\omega)|^2 = K\frac{\sin^2\left(\frac{\omega T'}{2}\right)}{\left(\frac{\omega T'}{2}\right)^2}.$$

In Figure 82 calculations are presented for the selection of the most effective filter for harmonic analysis when studying short-period variations.

In Figure 83 the distribution of days (separately in universal and asymptotic times) is given relative to the time of the maximum during 1964 for the stations of Deep River, Dallas, Sulphur, Calgary, Climax, Norikura, Wilkes, Washington and Mawson. From Figure 83 shows that the majority of days have the time of the maximum (in universal time) scattered in a broad interval. In asymptotic time, for the majority of days the time of the maximum lies between 3-5 hours.

In Figure 84 the time of the semidiurnal variation maximum presented from 1953 through 1965. The most complete and systematic data, as is seen from Figure 84, are from the second half of 1957. One can say that the time of the maximum in the solar activity minimum was shifted by 40-60 minutes to a later time relative to the solar activity maximum. Here it is difficult to draw any kind of specific conclusions, since the data were averaged over a number of stations, independently of the cutoff rigidity of each station. But, on the average, during the last 11 years the time of the maximum of the semidiurnal variation lay between 3-5 hours.

In Figure 85 histograms are presented which show the distribution of the amplitudes by days. It is seen that at the high-latitude stations the amplitude basically has the value 0.05-0.1%, and increases with an increase of the rigidity threshold (for example, at Norikura the amplitude reached 0.3%), which does not contradict the data obtained in [52] for the period of the /88 solar activity maximum.

In Figure 86 the directions of the semidiurnal anisotropy are shown in a harmonic diagram. One can see that no noticeable change in the direction of anisotropy is observed with a change in the solar activity cycle.

Let us discuss the question of the semidiurnal anisotropy in disturbed periods.

We mentioned the fact above that in a number of cases in magnetically disturbed periods the amplitude of the semidiurnal variation increased, and

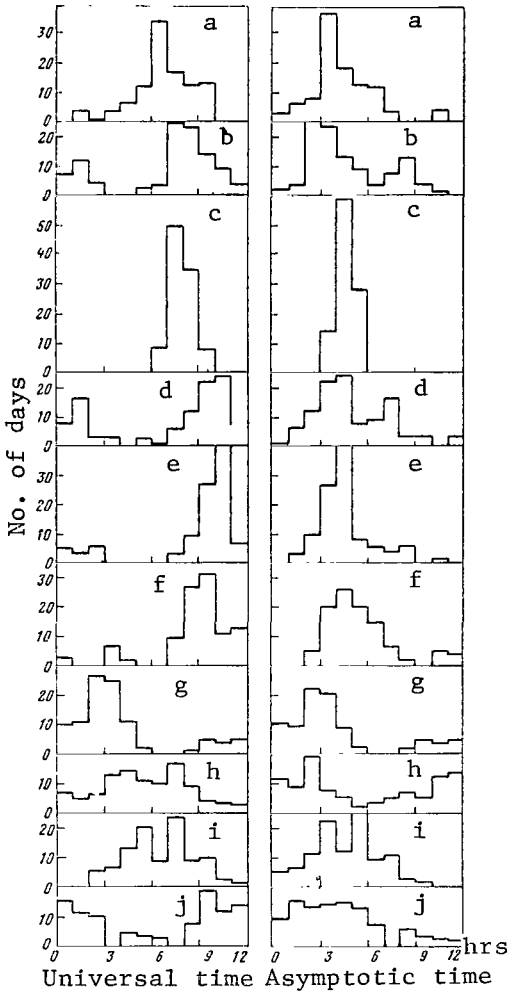


Figure 83. Distribution of days relative to the time of the semidiurnal variation maximum in universal time (to the left) and in asymptotic time with consideration of the influence of the geomagnetic field on the trajectory of particles (to the right).

a - Deep River; b - Churchill; c - Dallas; d - Sulphur; e - Calgary; f - Climax; g - Norikura; h - Wilkes; i - Washington; j - Mawson.

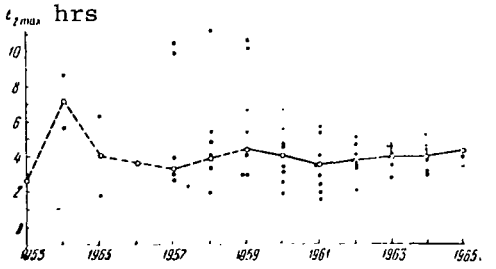


Figure 84. Time of the semidiurnal variation maximum during the period 1953-1965.

1 - for individual stations;
2 - averaged for all stations.

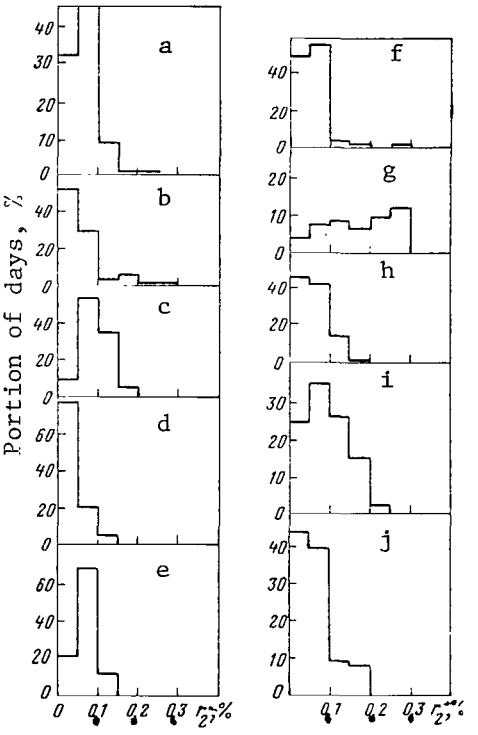


Figure 85. Histograms of the distribution of semidiurnal variation amplitudes by days at various stations.

The designations of the stations are the same as in Figure 83.

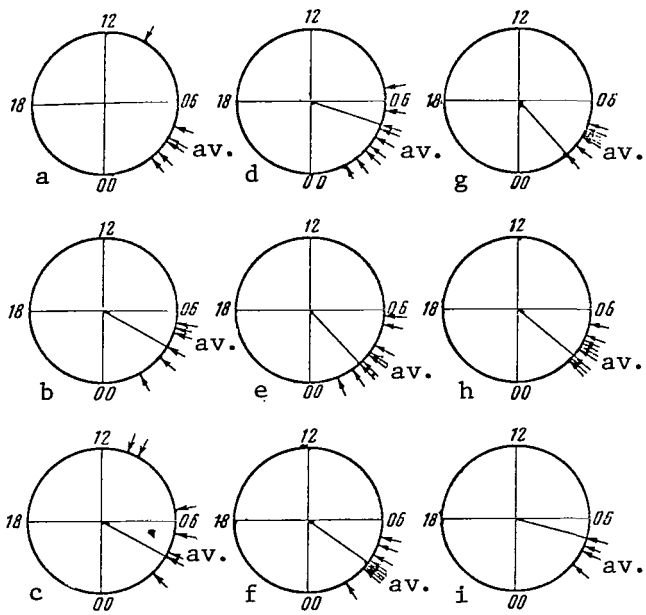


Figure 86. Direction of semidiurnal anisotropy in 1957-1965 (a-i)

The arrows indicate the results for the separate stations; av. - the average value; the vector drawn from the arrow is for the data of the station at Deep River.

the time of the maximum sharply changed both toward earlier hours and also toward later hours. /89

The authors of [99-102], using the method of autocorrelation, found that at sea level the main part of the semidiurnal variation (∿65%) is of meteorologic origin. At mountain level, on the other hand, the main part of the semidiurnal variation is of extra-atmospheric origin, but in the latter case the variation is irregular. An analysis was made in [99] for the period from October 14 through November 5, 1957, for the stations Norikura, Climax, Washington, Herstmonseaux, Lincoln and Leeds, which recorded the neutron component of cosmic ray intensity.

In conclusion to this section, let us investigate the change in amplitude and phase of the semidiurnal variation in a minimum of solar activity (1964). In Figure 87 the results of a harmonic analysis are presented, based on the observational data at the stations Churchill, Deep River and Dallas. The times of the maximum and the amplitude were calculated on the basis of data averaged over five days. From Figure 87 it is seen that a significant scatter of r_2 and $t_{2\ max}$ occurs, and there is no definite law

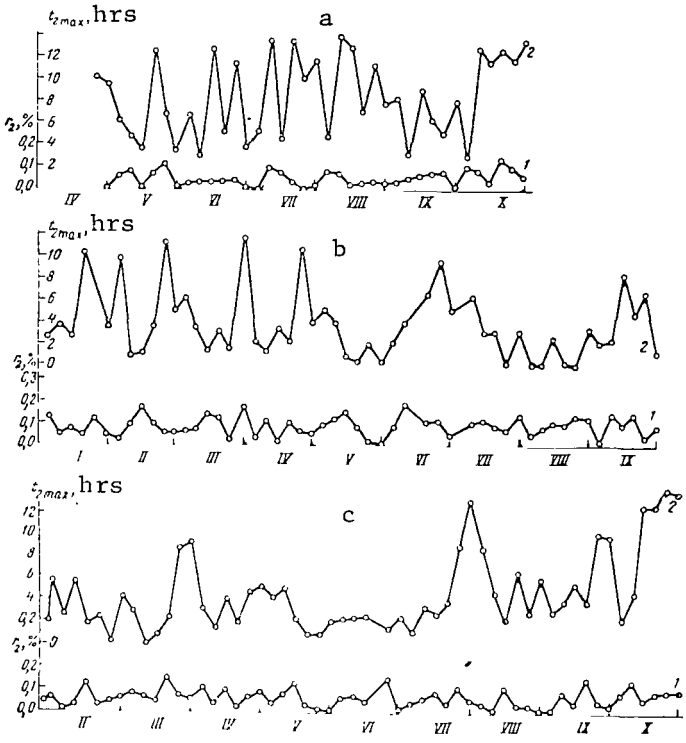


Figure 87. Change in amplitude (1) and phase (2) of the second harmonic in the minimum of solar activity of 1964 based on the observations at the stations:

a - Churchill; b - Deep River; c - Dallas.

governing the behavior of the change in r_2 and $t_{2\ max}$ with time. Also, no synchronous change of r_2 and $t_{2\ max}$ is observed at the stations mentioned above. /91

CHAPTER III

THE FUNDAMENTAL LAWS GOVERNING THE BEHAVIOR OF THE SOLAR-DIURNAL AND SEMIDIURNAL VARIATIONS AND A DISCUSSION OF THE MECHANISMS CAUSING THESE VARIATIONS

1. Solar-Diurnal Variations of Cosmic Rays and Their Energy Spectrum

Let us discuss the fundamental laws governing the change in solar-diurnal variations with the cycle of solar activity. /92

1. The amplitude of the solar-diurnal variation at the low and middle latitudes decreases with a decrease in solar activity. At the high-latitude stations, the amplitude of the solar-diurnal variations increases slightly. This conclusion shows that it is impossible to make a judgment about the change in diurnal variation in time based on data for various periods which were obtained at one or two points.

2. The energy spectrum of the diurnal variations has a power-law form (with an exponent ~ 0.4) and does not change with the cycle of solar activity. This result is obtained from the neutron component data recorded at the surface of the earth (at sea level and at higher elevations [54]). In [53], on the basis of these same data, results were obtained which showed that the form of the energy spectrum does not change with the cycle of solar activity, but the spectrum becomes harder — that is, the exponent equals zero. We indicated that the discrepancy in the results is a result of the difference in the methodological approach and the large approximations which

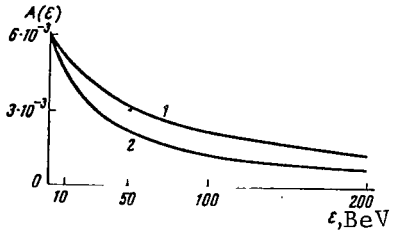


Figure 88. Change with time of the diurnal anisotropy energy spectrum in accordance with [47].

1 - at the maximum of solar activity (b = 60 BeV); 2 - at the minimum of solar activity (b = 30 BeV).

were employed in [53]. But the main factor, in our opinion, is the fact that the energy spectrum form does not change with the cycle of solar activity. As regards to Reference [47], where a softening of the anisotropy energy spectrum was indicated with a decrease of the solar activity, it occurs to us that the conclusion presented is incorrect. The author of [47] indicated that the energy spectrum had a form $A(\varepsilon) = 6 \cdot 10^{-3} \frac{b}{b+\varepsilon}$, and b at the solar activity maximum equals 60 BeV and at the minimum — b = = 30 BeV. /92

In Figure 88 values of $A(\varepsilon)$ are presented up to $\varepsilon = 2 \cdot 10^{11}$ BeV when b = 30 and 60 BeV. The results were obtained from data on the hard component which were recorded at various levels of the earth. When the data on the μ-meson component are processed, large errors are possible due to the introduction of a temperature correction (up to the present a perfect method for introducing the correction has not been developed and there are no systematic data on the temperature values). Errors may also be due to inexact coupling coefficients for particles of very high energies.

3. The lower boundary of the energy spectrum was shifted from 6-7 BeV at the maximum of solar activity to ∿2 BeV at the minimum.

4. The phase of the solar-diurnal variation from 1957 through 1965 was shifted to a later time by no more than one hour, and had a weak dependence on sunspot number.

5. During magnetically disturbed periods, basically the amplitude is increased and the time of the maximum is shifted to earlier hours. However,

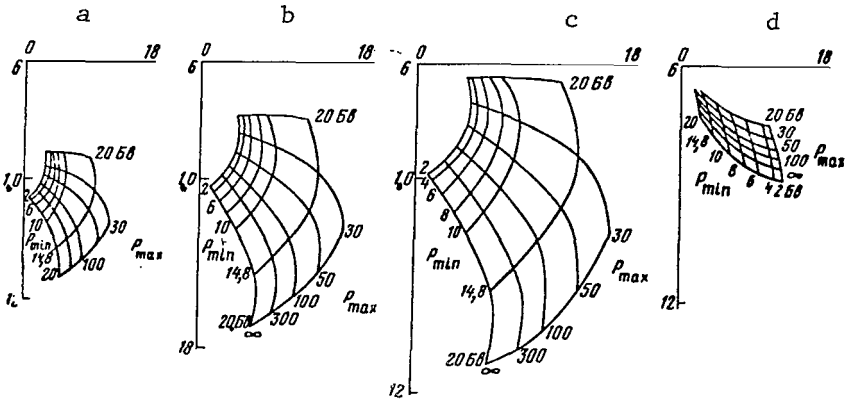


Figure 89. Results of calculating the diurnal variation vector on a harmonic diagram with an exponent of the energy spectrum $\gamma = 0$, the lower boundary of the spectrum P_{min} = 2-20 BeV, and the upper boundary of the spectrum P_{max} = 20 - ∞ BeV. The calculations were carried out for geomagnetic latitudes of 40° (a), 30° (b), 20° (c) and 60° (d).

there are a number of cases when the amplitude remains constant or even decreases, and the time of the maximum is shifted to later hours.

A rather high correlation of the solar variation amplitude with the sunspot number was observed at the high-latitude stations and with the K_p index at the low-latitude stations.

During certain Forbush effects, the energy spectrum of the cosmic ray anisotropy was slightly softened, which indicates an additional (near) source of diurnal anisotropy.

In Figure 89, data are presented on the theoretical calculations in [92] of the diurnal variation vector with a spectral exponent $\gamma = 0$ when the lower limit of the spectrum (P_{min}) equals 2-20 BeV, and the upper limit of the spectrum (P_{max}) ranges from 20 BeV up to infinity.

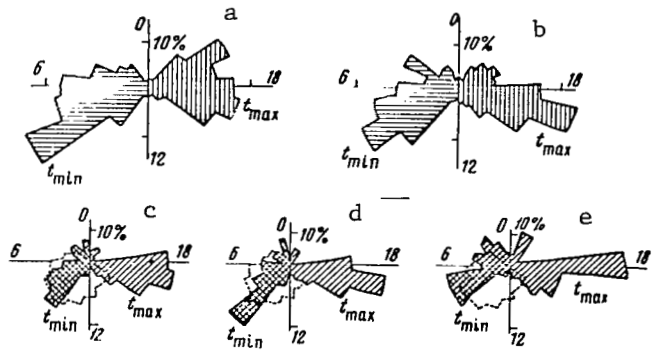


Figure 90. Values of t_{max} and t_{min} calculated for each day

a and b - during 154 days in 1964 based on data of stations at Sulphur and Calgary, respectively; c - based on data of the station at Deep River for the period November 27, 1963-February 17, 1964; d and e - based on data of the station at Deep River when $t_{max} - t_{min} \leq 9$ hours and when $t_{max} - t_{min} \approx 10$-12 hours, respectively.

2. Semidiurnal Variations of the Cosmic Rays

A semidiurnal variation is observed both in the period of the maximum and in the period of the minimum solar activity, but the amplitude and phase remain constant. No definite law governing the behavior as a function of solar and geomagnetic activity is observed.

The nature of the semidiurnal variation at the present time is unclear, at least unequivocally. Nevertheless, one can point to some possible mechanisms. In [103-108] /93

the change in anisotropy was analyzed, and it was compared with the change in the interplanetary magnetic field and the parameters of the solar wind. In [103, 104] based on the data of neutron supermonitors, studies were conducted of the time of the maximum and the time of the minimum of the solar-diurnal variations. The authors of [103] indicated that different mechanisms acting in different directions were responsible for t_{min} and t_{max}. The amplitude differences (positive and negative with respect to a day) and the differences t_{max} and t_{min} (for each day) changed from day to day as a function of the solar wind parameters. This phenomenon showed up even in the averaged data in [107] and is very clearly seen in the day-to-day data (Figure 90).

The energy spectrum of the semidiurnal variation has a power-law form with a positive exponent close to one. /94

CHAPTER IV

THE MECHANISM OF THE FORMATION OF COSMIC RAY ANISOTROPY

1. General Remarks

Questions concerning intensity modulation and formation of galactic cosmic ray anisotropy in interplanetary space were discussed in many works in which attention was paid to the radial motion of the plasma from the sun with magnetic nonuniformities against the background of regular fields, whose intensity near the sun was 1 - 2 oersted. It decreased with increasing distance from the sun as r^{-2} for the radial component of the field and as r^{-1} for the azimuthal component [1, 2, 81, 82, 85, 86, 108 - 127]. /95

From data on the 11-year variations in cosmic rays, from observations of the propagation of solar cosmic rays, and from direct measurements of the magnetic fields in interplanetary space it follows that the transport path for the scattering of particles in interplanetary space is much shorter than the dimensions of the system. If one also considers that the relative amplitude of the observed anisotropy is much smaller than one, then one should take the model of anisotropic diffusion as the most general mechanism for the solar-diurnal variation of cosmic rays. Below, we will investigate this model in detail in a form proposed in [128]. But here let us note that it is applicable for particles in broad rigidity intervals ($0.2 - 0.5$ BeV $\lesssim R \lesssim$ $30 - 100$ BeV). For particles of very small energies with $R \lesssim 0.2 - 0.5$ BeV, their radius of curvature in the energy magnetic fields becomes substantially smaller than the dimensions of the field nonuniformities. The motion becomes adiabatic, and instead of the expected scattering by the nonuniformities, a "leakage"

of the particles takes place along spirals which are wound on the force lines of the magnetic fields. For very high energy particles, the transport path for the scattering becomes comparable to the dimensions of the system, and in this case a more rigorous investigation is necessary based on the kinetic equation. It must be also emphasized that the indicated limits are not constant, but change during the cycle of solar activity in connection with the substantial change in modulation region parameters. Thus, with a transition from a maximum to a minimum of solar activity, a substantial decrease in the dimensions of the modulation region takes place, as well as an increase in the transport path for the scattering of particles of the same rigidity. Accordingly, the indicated upper limit of applicability of the anisotropy diffusion approximation must be substantially reduced with the transition from the maximum to the minimum of solar activity. As regards the lower limit, there are still no reliable data concerning the character of its change with the cycle of solar activity. But in any case these limits completely overlap that rigidity interval covered by the experimental data in the first three chapters of this work (the only possible exceptions are the data concerning the anisotropy of particles of very high energies which were observed deep beneath the earth).

2. The Fundamental Equations in the Approximation of Anisotropic Diffusion

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Let the density of the galactic cosmic rays in interplanetary space be $n(r, \theta, \varphi, R, Z, t)$, where r, θ, φ are the spherical coordinates with the center at the sun; R and Ze are the hardness and charge of the particles; t is the time. Then in the diffusion approximation the density n of galactic cosmic rays with a rigidity R and a charge Ze will be determined by the equation

$$\frac{\partial n}{\partial t} + \sum_{\alpha=1}^{4} \frac{\partial j_\alpha}{\partial x_\alpha} = F(r, \theta, \varphi, R, Z, t) \qquad \text{(IV.1)}$$

taking into account the boundary and initial conditions which are determined by the specific problem of the variations being studied. It is assumed that

the energy density of the cosmic particles in interplanetary space is much less than the energy density of the magnetic fields and the kinetic energy of the plasma motion, so that the reciprocal action of the cosmic radiation under conditions in interplanetary space can be neglected. One should note that for galactic cosmic rays, at distances of the order of the radius of the earth's orbit, this is fulfilled with a large margin. This condition may break down only at great distances, since — as distance to the sun increases — the density of the galactic cosmic particles increases. However, the energy density of the plasma motion and of the magnetic field motion decreases at least more rapidly than r^{-2}. For powerful solar bursts of cosmic rays, this condition is fulfilled (evidently only with rare exceptions)[1].

In Equation (IV.1) F is the source function, j_α are the components of the flux of particles along r, θ, φ and R. Let us consider that with a anisotropic diffusion the spatial flux is

$$j_i = -\sum_{k=1}^{3} \varkappa_{ik} \frac{\partial n}{\partial x_k} + u_{\mathrm{dr},i}\, n, \tag{IV.2}$$

where κ_{ik} is the diffusion tensor coefficient and $u_{dr,i}$ is the drift velocity of the cosmic rays in interplanetary space. In Chapter IV it will be shown that the u_{dr} which arises as a result of the radial motion of the plasma emerging from the rotating sun will contain the components $u_{dr,r}$, $u_{dr,\theta}$ and $u_{dr,\varphi}$. Then expression (IV.2) may be rewritten in the spherical coordinate system at the center of the sun:

$$j_r = -\varkappa_{rr}\frac{\partial n}{\partial r} - \frac{\varkappa_{r\theta}}{r}\frac{\partial n}{\partial \theta} - \frac{\varkappa_{r\varphi}}{r\sin\theta}\frac{\partial n}{\partial \varphi} + u_{\mathrm{dr},r}\, n, \tag{IV.3a}$$

$$j_\theta = -\varkappa_{\theta r}\frac{\partial n}{\partial r} - \frac{\varkappa_{\theta\theta}}{r}\frac{\partial n}{\partial \theta} - \frac{\varkappa_{\theta\varphi}}{r\sin\theta}\frac{\partial n}{\partial \varphi} + u_{\mathrm{dr},\theta}\, n, \tag{IV.3b}$$

$$j_\varphi = -\varkappa_{\varphi r}\frac{\partial n}{\partial r} - \frac{\varkappa_{\varphi\theta}}{r}\frac{\partial n}{\partial \theta} - \frac{\varkappa_{\varphi\varphi}}{r\sin\theta}\frac{\partial n}{\partial \varphi} + u_{\mathrm{dr},\varphi}\, n. \tag{IV.3c}$$

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[1] According to [129] when cosmic particles interact with magnetized plasma, there arises in particular a beam instability which leads to a decrease in the diffusion coefficient and to an increase in particle scattering.

Now let us find the flux $j_R = ndR/dt$ along the rigidity axis which is due to the fact that — when there is radial divergence of the magnetic nonuniformities from the sun — a systematic loss of energy by the particles takes place because of the preferential scattering associated with overtaking collisions (in the directions θ and φ) [124, 130]. Since with each collision the energy ε of the particle is reduced on the average by $\Delta\varepsilon = -\varepsilon v \Delta u/c^2$ where $\Delta u = u\Lambda/r$, and the time between collisions is $\Delta t = \Lambda/v$, and considering that the energy decrease takes place only for directions perpendicular to r, we obtain

$$\frac{d\varepsilon}{dt} = -\frac{2}{3}\frac{\varepsilon v^2}{c^2}\frac{u}{r}. \qquad \text{(IV.4)}$$

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Since

$$\varepsilon = Ze\sqrt{R^2 + \left(\frac{Am_0c^2}{Ze}\right)^2}; \quad d\varepsilon = \frac{ZeRdR}{\sqrt{R^2 + \left(\frac{Am_0c^2}{Ze}\right)^2}}; \qquad \frac{v^2}{c^2} = \frac{R^2}{R^2 + \left(\frac{Am_0c^2}{Ze}\right)^2}, \qquad \text{(IV.5)}$$

we obtain

$$\frac{dR}{dt} = -\frac{2}{3}\frac{u}{r}R. \qquad \text{(IV.6)}$$

Substituting equations (IV.3) and (IV.6) into (IV.1), we find the fundamental equation for studying the modulation effects of galactic cosmic rays in interplanetary space and for the propagation of solar cosmic rays:

$$\begin{aligned}\frac{\partial n}{\partial t} &- \frac{1}{r^2}\frac{\partial}{\partial r}\left(-r^2 u_{dr,r} n + r^2 \varkappa_{rr}\frac{\partial n}{\partial r} + r\varkappa_{r\theta}\frac{\partial n}{\partial \theta} + \frac{r\varkappa_{r\varphi}}{\sin\theta}\frac{\partial n}{\partial \varphi}\right) - \\ &- \frac{1}{r\sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta\varkappa_{\theta r}\frac{\partial n}{\partial r} + \frac{\sin\theta\varkappa_{\theta\theta}}{r}\frac{\partial n}{\partial \theta} + \frac{\varkappa_{\theta\varphi}}{r}\frac{\partial n}{\partial \varphi} - \sin\theta\cdot u_{dr,\theta} n\right) - \\ &- \frac{1}{r\sin\theta}\frac{\partial}{\partial \varphi}\left(\varkappa_{\varphi r}\frac{\partial n}{\partial r} + \frac{\varkappa_{\varphi\theta}}{r}\frac{\partial n}{\partial \theta} + \frac{\varkappa_{\varphi\varphi}}{r\sin\theta}\frac{\partial n}{\partial \varphi} - u_{dr,\varphi} n\right) - \\ &- \frac{2}{3}\frac{u}{r}\frac{\partial}{\partial R}(Rn) = F(r, \theta, \varphi, R, Z, t).\end{aligned} \qquad \text{(IV.7)}$$

3. Determining the Diffusion Tensor in Interplanetary Space

In order to determine κ_{ik} one must bear in mind the following facts.

1. The electromagnetic conditions in interplanetary space which are determined in the final analysis by the tensor of anisotropic diffusion κ_{ik} and by the velocity of motion of the plasma u do not remain constant, but vary in time. Accordingly, these changes are delayed by a time $t_{del} \approx r/u$ relative to the processes on the sun producing the fluxes of plasma. If one designates the factor controlling the ejection of the plasma from the sun by S (sunspot number, chromosphere flares, calcium flocculi, etc.), then $\kappa_{i,k}$ at the distance r from the sun will be

$$\varkappa_{i,k} = \varkappa_{i,k}(r, S(t - r/u)). \tag{IV.8}$$

2. Since the kinetic energy density of the plasma being ejected by the sun is much larger than the density of the magnetic fields connected with it (this relationship — which is valid according to direct measurements in the vicinity of the earth's orbit — must be fulfilled also at great distances from the sun, since the kinetic energy density decreases by $\sim r^{-2}$ and the density of the magnetic energy decreases more rapidly, possibly even as $\sim r^{-4}$ if the field basically is quasiradial). We may then expect that the plasma motion basically is radial. Then the locus of the parts of the plasma which were expelled from a single region on the sun is, due to rotation of the sun with an angular velocity $\Omega = 2\pi/T$ (where $T \approx 27$ days weakly depends on the polar angle θ), an Archimedes spiral

$$r - r_{\odot} = \frac{u(\theta_{\odot}, \varphi_{\odot})}{\Omega(\theta_{\odot})}(\varphi - \varphi_{\odot}) = a(\varphi - \varphi_{\odot}), \tag{IV.9}$$

where $\theta_{\odot}$ and $\varphi_{\odot}$, respectively, are the polar angle and the heliolongitude of the region generating the plasma on the surface of the sun $r_{\odot}$. The large-scale magnetic field will have a tendency to extend along these spirals. However, since $a(\theta_{\odot}, \varphi_{\odot})$ can change from region to region on the surface of the sun, this leads to a complex interaction of the solar plasma and magnetic fields. This may serve as one of the reasons for the production of non-uniformities of the magnetic field which move radially out from the sun. /98

3. The angle between the magnetic force lines and the direction of the radial motion of the magnetic nonuniformities

$$\psi = \arctan\left[\frac{(r - r_\odot)\,\Omega(\theta_\odot)}{u(\theta_\odot, \varphi_\odot)}\right] \qquad \text{(IV.10)}$$

determines the transformation of the tensor of anisotropic diffusion κ_{ik}.

4. In the coordinate system, where the direction of the force lines of the interplanetary magnetic field at a certain point r, θ, φ is taken as the OX axis, the tensor is

$$\bar{\kappa}_{ik} = \kappa_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & [1 + (\omega\tau)^2]^{-1} & -\frac{\omega\tau}{1 + (\omega\tau)^2} \\ 0 & \frac{\omega\tau}{1 + (\omega\tau)^2} & \frac{1}{1 + (\omega\tau)^2} \end{pmatrix}, \qquad \text{(IV.11)}$$

where $\tau = \Lambda/v$ is the average time between collisions; $\omega = \frac{ZeH}{Mc}$ is the Larmor frequency of the particle motion with a charge Ze and a mass $M = M_0 (1 - v^2/c^2)^{-1/2}$ in the large-scale field H. Considering that Λ depends on the hardness of the particles $R = cp/Ze$, and the radius of curvature in the magnetic field H is $\rho = R/300\,H$ (if R is in volts and H is in gauss, then ρ is in centimeters) we obtain

$$\omega\tau = \Lambda/\rho = \frac{300\,\Lambda(R)\,H}{R}, \qquad \text{(IV.12)}$$

that is, $\omega\tau$ is a function only of R and does not depend on the charge of the particle Ze and the velocity v. Substituting (IV.12) into (IV.11) we obtain

$$\bar{\kappa}_{ik} = \kappa_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & \alpha_1 & -\alpha_2 \\ 0 & \alpha_2 & \alpha_1 \end{pmatrix}, \qquad \text{(IV.13)}$$

where

$$\alpha_1 \equiv \frac{R^2}{R^2 + 9\cdot 10^4 \Lambda^2 H^2}; \quad \alpha_2 \equiv \frac{3\cdot 10^2 \Lambda H R}{R^2 + 9\cdot 10^4 \Lambda^2 H^2}. \qquad \text{(IV.14)}$$

Let us note that since $H \approx H_\odot (r_\odot / r)^2$ then when $\Lambda \sim$ const (that is, Λ does not depend on r) the term $\Lambda^2 H^2 \sim r^{-4}$ also rapidly decreases with the distance from the sun. Therefore, starting with a certain r_1 one may consider that $3 \cdot 10^2$ $\Lambda H \ll R$ and in accordance with (IV.14) $\alpha_1 \to 1$, $\alpha_2 \to 0$. One should also expect the same when $\Lambda \sim r$, since in this case $\Lambda^2 H^2 \sim r^{-2}$ and it rather rapidly decreases with an increase in r. Thus, in a large region of space far from the sun one may consider the diffusion to be isotropic and set $\varkappa = \varkappa_0$.

5. We may show that the determinant of the transformation of a_{ik} from the coordinate system connected with the magnetic force lines to the system of coordinates r, θ, φ has the form

$$a_{ik} = \begin{pmatrix} C_1 & 0 & -C_2 \\ 0 & 1 & 0 \\ C_2 & 0 & C_1 \end{pmatrix}, \tag{IV.15}$$

where

$$C_1 = (1 - \sin^2 \psi \sin^2 \theta)^{1/2}; \quad C_2 = \sin \psi \sin \theta. \tag{IV.16}$$

In the system r, θ, φ the tensor of anisotropic diffusion is /98

$$\varkappa_{ik} = \sum_{m,\, n} a_{mi} a_{nk} \bar{\varkappa}_{mn} = \varkappa_0 \begin{pmatrix} C_1^2 + \alpha_1 C_2^2 & C_2 \alpha_2 & -C_1 C_2 (1 - \alpha_1) \\ -C_2 \alpha_2 & \alpha_1 & -\alpha_2 C_1 \\ C_1 C_2 (1 - \alpha_1) & \alpha_2 C_1 & C_2^2 + \alpha_1 C_1^2 \end{pmatrix}. \tag{IV.17}$$

It is easy to see that in the plane of the helioequator ($\theta = \pi/2$):

$$\varkappa_{ik} = \varkappa_0 \begin{pmatrix} \cos^2 \psi + \alpha_1 \sin^2 \psi & \alpha_2 \sin \psi & -\sin \psi \cos \psi (1 - \alpha_1) \\ -\alpha_2 \sin \psi & \alpha_1 & -\alpha_2 \cos \psi \\ \sin \psi \cos (1 - \alpha_1) & \alpha_2 \cos \psi & \sin^2 \psi + \alpha_1 \cos^2 \psi \end{pmatrix}. \tag{IV.18}$$

One should keep in mind that in (IV.17) and (IV.18) ψ is a function of r, $\theta_\odot$ and $\varphi_\odot$ in accordance with (IV.10), and $\varkappa_0 = \frac{v\Lambda}{3}$ is a function of t - r/u, θ and φ.

4. DETEPMINING DRIFT VELOCITY in Interplanetary Space

With the radial motion of plasma having the magnetic field **H** with a velocity $\mathbf{u} = u\mathbf{r}/r$ an electric field **E** arises in the sun-stars system of coordinates. In this system of coordinates the charged particles of the cosmic radiation under the action of **E** and **H** will drift with a velocity

$$\mathbf{u}_{dr} = \frac{\mathbf{H} \times (\mathbf{u} \times \mathbf{H})}{H^2} = \frac{u\mathbf{r}}{r} - \frac{u(\mathbf{r}\mathbf{H})\mathbf{H}}{H^2 r}. \qquad \text{(IV.19)}$$

First let us investigate the drift under the action of the regular spiral-like interplanetary field. Since in this case the angle between **r** and $\mathbf{H}_0$ is determined by expression (IV.10), then on the basis of (IV.19) we obtain for the components of the drift velocity (independent of the direction in which $\mathbf{H}_0$ is directed — toward the sun or away from the sun):

$$(u_{dr,\ r})_{reg} = \frac{u\Omega^2 (r - r_\odot)^2}{u^2 + \Omega^2 (r - r_\odot)^2}; \quad (u_{dr,\ \theta})_{reg} = 0; \quad (u_{dr,\ \phi})_{reg} = \frac{u^2 \Omega (r - r_\odot) \sin\theta}{u^2 + \Omega^2 (r - r_\odot)^2}. \qquad \text{(IV.20)}$$

Now let us investigate the other extreme case. Let us assume that the interplanetary field is only a collection of nonuniformities, in which the direction of the magnetic field **h** may be in any arbitrary direction with equal probability. Let the angle between **r** and **h** be ξ (measured counterclockwise from **r** to **h**). Then by averaging (IV.19) over all possible directions of **h**, we obtain:

$$(u_{dr,\ r})_{turb} = 2/3\ u; \quad (u_{dr,\ \phi})_{turb} = (u_{dr,\ \theta}) = 0. \qquad \text{(IV.21)}$$

When there are field nonuniformities against a background of a large-scale regular field, considering (IV.20) and (IV.21) and designating the relative role of the large-scale field by $\beta \sim \frac{H_0}{H_0 + h}$, we obtain

$$u_{dr,\ r} = \frac{\beta u \Omega^2 (r - r_\odot)^2}{u^2 + \Omega^2 (r - r_\odot)^2} + \frac{2(1 - \beta) u}{3}; \quad u_{dr,\ \varphi} = \frac{\beta u^2 \Omega (r - r_\odot) \sin\theta}{u^2 + \Omega^2 (r - r_\odot)^2}; \quad u_{dr,\ \theta} = 0. \qquad \text{(IV.22)}$$

5. Time Variations and Spatial Anisotropy of Cosmic Rays

Substituting (IV.17) and (IV.22) into (IV.7), we obtain an equation which determines the space-time change in cosmic ray density. Using the boundary and initial conditions, it is possible to find by means of this equation the desired function $n(r, \theta, \Phi, R, Z, t)$.

Substituting n which was found, (IV.17) and (IV.22) into (IV.3), let us then find the spatial fluxes of particles which determine the anisotropy of cosmic rays: in the radial direction — the so-called 12- and 24-hour anisotropy (j_r/nv); in the direction perpendicular to the plane of the helioequator — the so-called north-south asymmetry (j_θ/nv); in the direction along the earth's orbit — the 6- hour and 18-hour anisotropy (j_φ/nv). /100

When comparing the theoretical results with the experimental data, it is necessary to keep in mind that Equation (IV.7) gives results relative to the coordinate system connected with the helioequator. The conversion for the case of observations on the rotating earth, whose heliolatitude changes during the course of the year and whose spin axis is inclined to the plane of the ecliptic at an angle of 66.5°, may be carried out with the equations in [131].

Now let us discuss the region of applicability of Equation (IV.7). It is known that the approximation of anisotropic diffusion is better applied to the description of the process, the slower the density and fluxes of the particles change at a distance on the order of the mean free path. For the estimates, one may use the criteria:

$$\frac{1}{n}\frac{\partial n}{\partial x_\alpha}\Lambda \ll 1;\ \frac{1}{j}\frac{\partial j}{\partial x_\alpha}\Lambda \ll 1. \qquad \text{(IV.23)}$$

In all the cases of galactic cosmic ray modulation of practical interest, the criteria (IV.23) are fulfilled. Actually according to measurements [132] in

interplanetary space in the region of the earth's orbit, for particles with an energy $\gtrsim$ 10 MeV the relative radial gradient of the cosmic ray intensity in 1962 was $\frac{1}{n}\frac{\partial n}{\partial r}\approx(12\pm4)$ %/1 a.u. But at this distance from the sun for such soft particles, according to a study of the propagation of solar cosmic rays [133], $\Lambda \sim 10^{12}$ cm. Consequently, in the radial direction in 1962 $\frac{1}{n}\frac{\partial n}{\partial r}\Lambda \lesssim$ 0.01. For high-energy particles Λ increases, but in accordance with [2], the relative gradient must decrease by the same factor, so that the estimate in practice must not strongly depend on the particle energy. At the solar activity maximum the relative gradient must increase severalfold (this follows from the experimental data for the 11-year variations of cosmic rays [134]), but Λ decreases somewhat, so that the criterion (IV.23) nevertheless is fulfilled. It is easy to show that criterion (IV.23) is equivalent to the condition $j/nv \ll 1$. But according to numerous studies of the diurnal variations in the entire radiation interval of hardnesses $j/nv \lesssim 0.01$, and only in specific periods of high Forbush effects, does j/nv reach 0.03 - 0.05. The approximation of anisotropic diffusion is not applicable when studying the question as to how the transformation of the anisotropic flux of galactic cosmic rays takes place when cosmic rays pass from the Galaxy into the solar system (the scattering leads to a decrease in the degree of anisotropy of galactic origin). In this case a kinetic investigation of the transformation of the distribution function f(r, v, t)is necessary. Such an investigation also is necessary when studying the angular distribution of solar cosmic rays in the initial phase after their generation in a chromosphere flare [135, 136]. An analysis shows that in all remaining cases of solar cosmic ray propagation in interplanetary space criteria (IV.23) are fulfilled, and the anisotropic diffusion approximation is completely applicable.

6. Diurnal Variation in the Model of Anisotropic Diffusion

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According to what was said above, the anisotropy vector A is determined in terms of the particle flux j as

$$A = 3\mathbf{j}(nv)^{-1}, \tag{IV.24}$$

where v is the particle velocity.

According to [137] when $r \gg r_\odot$ ($r_\odot$ is the radius of the corona from which point the solar wind emerges)

$$\Psi = \operatorname{arctg}(r\Omega u^{-1}); \; H_r = H_{r\odot} r_\odot^2 r^{-2}; \; H_\varphi = H_{r\odot} r_\odot \Omega u^{-1} r_\odot r^{-1} \sin\theta;$$
$$H_\theta = 0; \; H_\odot = H_{r\odot}(1 + r_\odot^2 \Lambda^2 u^{-2} \sin^2\theta)^{1/2};$$
$$H = H_\odot r_\odot r^{-1} \left(\frac{r_\odot^2 r^{-2} + r_\odot^2 \Omega^2 u^{-2} \sin^2\theta}{1 + r_\odot^2 \Omega^2 u^{-2} \sin^2\theta} \right)^{1/2}, \tag{IV.25}$$

where u is the velocity of the solar wind; $\Omega \approx 2.7 \cdot 10^{-6}$ rad/sec is the angular velocity of rotation of the sun (strictly speaking, Ω is not a constant quantity, but weakly depends on θ); the index $\odot$ means that the corresponding values refer to the region of the earth's orbit. Substituting (IV.25) into (IV.14) and (IV.16) and then the results obtained into (IV.17), we find:

$$\varkappa_{rr} = \frac{V\Lambda}{3} \left\{ 1 - \frac{9 \cdot 10^4 \sin^2\theta \Omega^2 \Lambda^2 H_\odot^2 r_\odot^4 \, [r^{-2} + \Omega^2 u^{-2} \sin^2\theta]}{(r^2\Omega^2 + u^2)\,]R^2(1 + r_\odot^2 \Omega^2 u^{-2} \sin^2\theta) + 9 \cdot 10^4 \Lambda^2 H_\odot^2 r_\odot^4 r^{-2}(r^{-2} + \Omega^2 u^{-2} \sin\theta)} \right\} \tag{IV.26}$$

$$\varkappa_{r\theta} = \frac{V\Lambda}{3} \frac{3 \cdot 10^2 r\Omega \sin\theta \Lambda R H_\odot r_\odot^2 r^{-1} (r^{-2} + \Omega^2 u^{-2} \sin^2\theta)^{1/2} (1 + r_\odot^2 \Omega^2 u^{-2} \sin^2\theta)^{1/2}}{(r^2\Omega^2 + u^2)^{1/2} [R^2(1 + r_\odot^2 \Omega^2 u^{-2} \sin^2\theta) + 9 \cdot 10^4 \Lambda^2 H_\odot^2 r^4 \, r^{-2}(r^{-2} + \Omega^2 u^2 \sin^2\theta)]}; \tag{IV.27}$$

$$\varkappa_{r\varphi} = \varkappa_{\varphi r} =$$
$$= \frac{V\Lambda}{3} \frac{9 \cdot 10^4 \Lambda^2 H_\odot^2 \Omega r_\odot^4 r^{-1} \sin\theta \, (r^2\Omega^2 \cos^2\theta + u^2)^{1/2} (r^{-2} + \Omega^2 u^{-2} \sin^2\theta)}{(r^2\Omega^2 + u^2)\,[R^2(1 + r_\odot^2 \Omega^2 u^{-2} \sin^2\theta) + 9 \cdot 10^4 \Lambda^2 H_\odot^2 r_\odot^4 r^{-2}(r^{-2} + \Omega^2 u^{-2} \sin^2\theta)]}; \tag{IV.28}$$

$$\varkappa_{\theta r} = \varkappa_{\theta\varphi} = \varkappa_{\varphi\theta} =$$
$$= -\frac{V\Lambda}{3} \frac{3 \cdot 10^2 \Lambda H_\odot R r_\odot^2 r^{-1} (r^2\Omega^2 \cos^2\theta + u^2)^{1/2} (r^{-2} + \Omega^2 u^{-2} \sin^2\theta)^{1/2} (1 + r_\odot^2 \Omega^2 u^{-2} \sin^2\theta)^{1/2}}{(r^2\Omega^2 + u^2)^{1/2} [R^2(1 + r_\odot^2 \Omega^2 u^2 \sin^2\theta) + 9 \cdot 10^4 \Lambda^2 H_\odot^2 r_\odot^4 r^{-2}(r^{-2} + \Omega^2 u^{-2} \sin^2\theta)]}; \tag{IV.29}$$

$$\varkappa_{\theta\theta} = \frac{V\Lambda}{3} \frac{R^2(1 + r_\odot^2 \Omega^2 u^{-2} \sin^2\theta)}{R^2(1 + r_\odot^2 \Omega^2 u^{-2} \sin^2\theta) + 9 \cdot 11^4 \Lambda^2 H_\odot^2 r_\odot^4 r^{-2}(r^{-2} + \Omega^2 u^{-2} \sin^2\theta)}; \tag{IV.30}$$

$$\varkappa_{\varphi\varphi} = \frac{V\Lambda}{3} \frac{R^2(1 + r_\odot^2 \Omega^2 u^{-2} \sin^2\theta) + 9 \cdot 10^4 \Lambda^2 \sin^2\theta H_\odot^2 r_\odot^4 \Omega^2 (r^2\Omega^2 + u^2)^{-1} (r^{-2} + \Omega^2 u^{-2} \sin^2\theta)}{R^2(1 + r_\odot^2 \Omega^2 u^{-2} \sin^2\theta) + 9 \cdot 10^4 \Lambda^2 H_\odot^2 r_\odot^4 r^{-2}(r^{-2} + \Omega^2 u^{-2} \sin^2\theta)}. \tag{IV.31}$$

In Expression (IV.3) for the particle flux vector, u_{dr} also are introduced which, with consideration of (IV.25), will be

$$u_{dr\ r} = \frac{\beta u \Omega^2 r^2}{u^2 + \Omega^2 r^2} + \frac{2(1-\beta)u}{3}; \quad u_{dr\ \phi} = \frac{\beta u^2 \Omega r \sin\theta}{u^2 + \Omega^2 r^2}; \quad u_{dr\ 0} = 0. \tag{IV.32}$$

where $\beta \sim H_0(H_0 + h)^{-1}$ is the parameter defining the relative role of the regular H_0 and irregular H components of the interplanetary field. Here it is assumed that the structure of the field is determined in accordance with (IV.25). Substituting (IV.25) - (IV.32) into (IV.3) and then into (IV.24), let us find the components of the anisotropy vector. Let us find the expected properties of the anisotropy in various cases.

7. Anisotropy in the Vicinity of the Earth's Orbit

First let us determine the properties of anisotropy in the vicinity of the earth ($r = r_\delta$, $\theta = \pi/2$). Assuming $u = 3 \cdot 10^7$ cm/sec. let us find $\Omega r_\delta = 4 \cdot 10^7$ cm/sec; $\Omega r_\delta / u = 1{,}33$; $\Psi_\delta = 53°$; $\Omega^2 r_\delta^2 (\Omega^2 r_\delta^2 + u^2)^{-1} = 0{,}64$; $1 + r_\delta \Omega^2 u^{-2} = 2{,}78$ Let us use $R_{c\delta} = 3 \cdot 10^2 \Lambda H_\delta$ and $p = R/R_{c\delta}$. Then on the basis of (IV.24) - (IV.32) we obtain the following in the Earth's orbit in the vicinity of the helioequator plane:

$$\varkappa_{rr} = \frac{V\Lambda}{3} \cdot \frac{0{,}36 + p^2}{1 + p^2}; \quad \varkappa_{r\theta} = \frac{V\Lambda}{3} \cdot \frac{0.8p}{1 + p^2}; \quad \varkappa_\varphi = \varkappa_{pr} = -\frac{V\Lambda}{3} \frac{0{,}8}{1 + p^2};$$
$$\varkappa_{\theta r} = \varkappa_{0\varphi} = -\varkappa_{\varphi\theta} = -\frac{V\Lambda}{3} \cdot \frac{p}{1 + p^2}; \tag{IV.33}$$
$$\varkappa_{00} = \frac{V\Lambda}{3} \cdot \frac{p^2}{1 + p^2}; \quad \varkappa_{\varphi\varphi} = \frac{V\Lambda}{3} \cdot \frac{0{,}64 + p^2}{1 + p^2};$$

Let us determine the quantity p. Because of a broad spectrum of nonuniformities, one should expect $\Lambda = aR$ [122]. Therefore

$$p = (3 \cdot 10^2 a H_\delta)^{-1}. \tag{IV.34}$$

Because from the analysis [133] of solar cosmic ray propagation from the flare of May 4, 1960, in the period of the initial anisotropic stage (based on a study of the solution

of the kinetic equation) it follows that in the vicinity of the earth's orbit $1.3\ v\lambda = 5\cdot10^{22}\ cm^2\cdot sec^{-1}$ for particles with an effective hardness of around 3 BeV (based on observations by means of terrestrial neutron monitors), then $a = \frac{5}{3}\cdot10^3$. Since according to the direct measurements of the interplanetary magnetic field $H_\delta = 5\cdot10^{-5}$ gauss, then $p = 4\cdot10^{-2}$. Then from (IV.33) it follows

$$\begin{gathered}\varkappa_{rr}\simeq 0{,}36\,\frac{V\Lambda}{3};\quad \varkappa_{r\varphi}=\varkappa_{\varphi r}\approx -0{,}8\,\frac{V\Lambda}{3};\quad \varkappa_{\varphi\varphi}\simeq 0{,}64\,\frac{V\Lambda}{3};\\ \varkappa_{r\theta}\simeq 0{,}032\,\frac{V\Lambda}{3};\quad \varkappa_{\theta r}=\varkappa_{\theta p}=-\varkappa_{\varphi\theta};\\ \varkappa_{r\theta}\simeq\varkappa_{\theta r}\approx\varkappa_{\theta\varphi}\approx\varkappa_{\varphi\theta}\approx\varkappa_{\theta\theta}\approx 0^*.\end{gathered}\tag{IV.35}$$

Now let us determine the particle drift velocity in the vicinity of the earth's orbit. Since $H_0 \sim h$ based on data of direct measurements, then by assuming $\beta \approx 0.5$ and with $u = 3\cdot10^7$ cm/sec we obtain:

$$u_{dr.r} = 2\cdot10^7\ \text{cm/sec};\quad u_{dr.\phi} = 0.7\cdot10^7\ \text{cm/sec};\quad u_{dr.\theta} = 0.\tag{IV.36}$$

Substituting (IV.35) and (IV.36) into (IV.3) and then into (IV.24) we obtain:

$$\begin{gathered}A_{r\delta}=-0{,}36\,\frac{\Lambda}{n}\,\frac{\partial n}{\partial r}+0{,}8\,\frac{\Lambda}{nr_\delta}\,\frac{\partial n}{\partial\varphi}+0{,}2\cdot10^{-2};\quad A_{\theta\delta}\approx 0;\\ A_{\varphi\delta}=0{,}8\,\frac{\Lambda}{n}\,\frac{\partial n}{\partial r}-0{,}64\,\frac{\Lambda}{nr_\delta}\,\frac{\partial n}{\partial\varphi}+0{,}07\cdot10^{-2}.\end{gathered}\tag{IV.37}$$

8. The Diurnal Variation and the Average Radial Gradient of Cosmic Ray Intensity

When analyzing the data averaged over a period longer than the period of rotation of the sun, the term $\partial n/\partial\varphi \to 0$ and Expressions (IV.37) are simplified. Let us consider further that there is a definite connection between j_r and the average intensity of the cosmic rays inside the sphere of radius r_δ: if $j_r > 0$, then n must decrease. Since the average values of the intensity (for example, the mean monthly or mean annual values) change with time relatively slowly, one is able to show that the average values of A_r must be small. /103

Actually in the course of the 11-year cycle of solar activity, the intensity of the neutron component varies on the average by no more than 10%

during $T \approx 1$ year, that is $4\pi r_\delta^2 j_r T \approx 0{,}1\, 4\pi/3 r_\delta^3 n$. Hence, $j_r \approx 0{,}1 r_\delta n/3T$ and $A_r \, 0{,}1 r_\delta / VT \sim 2 \cdot 10^{-6}$, whereas the observed diurnal variations are larger by almost three orders of magnitude ($\sim 0.1\%$). In the region of lesser hardnesses, the intensity changes are substantially larger, but in any case they do not exceed 100% per year which gives $A_r \leqslant 2 \cdot 10^{-5}$. This quantity also may be neglected. Thus, on the average, $A_{r\delta} \approx 0$, then from Expression (IV.37) for $A_{r\delta}$ it follows:

$$\frac{\Lambda}{n} \frac{\partial n}{\partial r} \approx 0{,}56 \cdot 10^{-2}. \tag{IV.38}$$

Now we can estimate the expected average radial gradient of the density in the earth's orbit:

$$\frac{r_\delta}{n} \frac{\partial n}{\partial r} \approx \frac{r_\delta}{\Lambda} \cdot 0{,}56\,\%/1\ a.e. \tag{IV.39}$$

If one assumes $\Lambda \approx aR$ where $a \approx 5/3 \cdot 10^3$ (see above), then

$$\frac{r_\delta}{n} \frac{\partial n}{\partial r} \approx \frac{5}{R}\,\%/1\ \text{a.u.},$$

which is in agreement with the changes in the radial gradient in the vicinity of the earth's orbit.

9. Average Diurnal Variation in the Vicinity of the Earth's Orbit

Substituting (IV.38) into (IV.37) with consideration of the fact that for the average variation dn/dy = 0, we obtain $A_{\varphi\delta} \approx 0{,}52\%$ with a direction to the anisotropy maximum at 18 hours. The physical meaning of the diffusion mechanism of this variation was discovered in the work of G. F. Krymskiy [82]: as a result of the solar wind, cosmic rays are carried away convectively from the solar system in a radial direction from the sun. This carrying away is compensated by the radial component of the diffusion flux which is directed

basically along the lines of force of the regular interplanetary field. The uncompensated tangential component also gives a fundamental average diurnal variation with a direction of 18 hours (a secondary flux in the direction of the earth's rotation around the sun).

10. Rapid Anisotropy Changes

Besides the smooth anisotropy changes, rapid changes are possible, for example, during Forbush effects. In this case the radial and azimuthal gradients sharply increase and change their direction, which will lead, in accordance with (IV.37), to sharp changes in $A_{r\delta}$ and $A_{\varphi\delta}$. Moreover, noticeable changes in wind velocity u also are possible, which lead to significant changes in the amplitude and phase of the diurnal variation (it is thus necessary to use Equations (IV.3), (IV.24) and (IV.26) — (IV.32)).

11. North-South Asymmetry

In accordance with (IV.37) $A_{\theta\delta} \approx 0$. However, this is only in the first approximation. First, in (IV.35) $\chi_{r\theta}$, $\chi_{\theta r}$, $\chi_{\theta\varphi}$, $\chi_{\varphi\theta}$, $\chi_{\theta\theta}$ are set equal to zero although strictly speaking they are, in accordance with (IV.33), one-two orders of magnitude smaller than the remaining components of the diffusion tensor. Second, with a breakdown of asymmetry or at a great distance from the plane of the helioequator, in accordance with the complete equations, $A_{\theta\delta}$ will also arise. Thus, a detailed analysis of the diurnal variations which are free from the influence of the atmosphere and the magnetic field is able to give valuable information concerning the cosmic ray gradients, the asymmetry of the solar wind, the transport path for scattering, and the variability of the conditions in interplanetary space.

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